Multicast Routing Algorithms and Failure Analyses for Low Earth Orbit Satellite Communication Networks

THESIS

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AFIT/GE/ENG/02-34

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In Partial Fulfillment of the

Requirements for the Degree of

Master of Science (Electrical Engineering)

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Jae Soong Lee

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ABSTRACT

In the rapidly changing environment of mobile communications, the importance of the mobile satellite (e.g., low earth orbit satellites (LEOsats)) networks will increase due to their global visibility and connection. Multicasting is an effective communication method in terms of frequency spectrum usage for a LEO network. It is devised to provide lower network traffic (i.e., one-to-many transmissions). This research examines the system performance of two dissimilar terrestrially-based multicasting protocols: the Distance Vector Multicast Routing Protocol (DVMRP) and the On Demand Multicast Routing Protocol (ODMRP). These two protocols are simulated in large group membership density and in the presence of satellite failures. Two different algorithms are developed and used to select critical satellites for degrading a LEO network constellation. The simulation results show that the ODMRP protocol successfully reconfigured routes in large group membership density areas and in satellite failure conditions. Results also show that the ODMRP provided reliable packet delivery. However, ODMRP showed an enormous end-to-end delay in severe satellite failure conditions. This result is attributable to the delayed route refreshing procedure of ODMRP. In contrast, the DVMRP suffered from broken routes and complexity in the large group membership density and in satellite failure conditions. It had a smaller packet delivery ratio than the ODMRP (approximately 85.5% versus 98.9% for the 80 user case). The DVMRP showed scalable and stable end-to-end delay under multiple failed satellite conditions. The large group membership density and the multiple satellite failure conditions provide a more complete assessment for these two protocols.

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Chapter 1: Introduction

1.1 Background

The Internet routes datagrams using a one-to-one (unicast) method. Unicast routing sends individual datagrams to every recipient. Unicast routing wastes bandwidth because multiple copies of the datagram must be sent. On the other hand, multicast routing sends a single datagram rather than multiple copies of a datagram. Multicast routing results in lower network traffic on the Internet.

As wireless mobile network technologies continue to develop, the mobility and reach of telecommunication services must be independent of user locations. The importance of the mobile satellite (e.g., low earth orbit satellites (LEO)) networks will increase due to the global visibility and connection.

Currently, multicasting communication service on the Internet assumes a static network environment instead of a mobile networks. Moreover, research on mobile networks has largely focused on unicast communications. In fact, multicast communications for mobile satellite networks is an open research area. In order to implement satellite networks that satisfy the demand for a lower network load and mobility, it is necessary to support multicast routing, possibly through multicasting Internet Protocol (IP) [Tho01].

1.2 Problem

The purpose of this research is to determine the effectiveness of various multicast routing protocols in LEO satellite networks. LEO satellite systems have mobile network topologies and this dynamic topology makes data routing difficult. In the mobile network research community, the problem of implementing IP has focused on the "nomadic hosts" and "ad-hoc networks" [Tho01]. In the nomadic hosts scenario, mobile IP supports mobile hosts on a network with fixed routers and topology. In Mobile Ad hoc Networks (MANETs), each mobile node operates both as a host and a router. The application of these two models to a dynamic satellite constellation provides a realistic multicast routing scenario for LEO satellite networks. This research simulates two multicast protocols under a nomadic hosts scenario and an ad-hoc network scenario.

1.3 Summary of Current Knowledge

This section introduces some standard multicast model and routing protocols. The mobile IP protocol is then examined. Current mobile multicast techniques are discussed as applied to nomadic hosts and ad-hoc networks. Finally, mobile satellite networks are discussed focusing on how information is routed via intersatellite links.

1.3.1 The IP Multicast model and routing protocols

Stephen Deering [Dee89] proposed a standard multicast model for the Internet protocol, in Request For Comment (RFC) 1112. RFC 1112 specifies the host extension

to support multicasting. This model has three characteristics, "IP-style semantics", "Open groups", and "Dynamic groups" [Tho01]. IP multicasting transmits an IP datagram to a host group. A multicast router then distributes a datagram to destination hosts. This multicast communications implies that source nodes know the multicast host group address to send datagrams, conversely multicast destination hosts in the group need to know the host group address in order to subscribe to them. A multicast router must keep track of group membership information to deliver a datagram. In order to accomplish this, an IP address space and group management mechanism is required. The address space defines multicast host group addresses as a Class D IP address. A class D address uses the entire 32 bits allocated for addressing and has "1110" as its highest order bits. The remaining 28-bits are called "multicast host group address" ranging from 224.0.0.0 to 239.255.255.255. The Internet Group Management Protocol (IGMP) provides the group management mechanism. According to Deering, "IGMP protocol is used by hosts to report their host group memberships to any immediately neighboring multicast routers" [Dee89]. The routers also use IGMP to discover which host groups have members on their attached local networks [Dee89].

Most existing multicast protocols can be categorized into source-based and core-based multicast tree routing protocols according to their routing architecture [WaH00]. A source-based multicast routing tree is rooted at a source node and connects to every destination node of the multicast group. The Distance Vector Multicast Routing Protocol (DVMRP), Protocol Independent Multicast Dense Mode (PIM-DM), and Multicast Open Shortest Path First (MOSPF) protocols are examples of the source-based multicast protocols. Core-based multicast routing is centered on a core router (termed

the Rendezvous Point (RP)) and extends to all group members. All source nodes for the multicast group share this tree. The Core-Based Multicast Tree (CBT), Protocol Independent Multicast Sparse Mode (PIM-SM), and Simple Multicast (SM) are examples of core-based multicast protocols.

1.3.2 Mobile IP

The goal of the Mobile IP design is to permit a host to change its attachment point to the network while maintaining all existing communications. In particular, Mobile IP provides a mechanism for routing IP packets to mobile hosts that may be connected to different networks while keeping their permanent IP address [Sol98]. As the Mobile IP name implies, its purpose is host mobility. The IETF Mobile IP Working Group (RFC 2002) defined a protocol to support a mobile host implementation. In mobile IP, hosts maintain a permanent IP address wherever they go. Packets are transmitted to the permanent address of the mobile host, namely the home agent address. If the mobile host is not in the home network, packets are encapsulated and forwarded to the mobile host's new address (foreign agent). When the mobile host is at a foreign network, it must register its new care-of-address with its home agent. Using these mechanisms, a mobile host can continue to communicate.

1.3.3 Mobile Multicast

It is becoming evident that the Internet must support mobile nodes that are nomadic or "roaming". In this scenario, a roaming host may be connected through various means to the Internet other than its well-known fixed-address domain space [Tho01].

The Internet Engineering Task Force (IETF) introduced a method of multicasting routing support for mobile hosts. This mechanism has been developed to provide the same connectivity for mobile hosts a remote networks as when they are connected to their home network. This method supports nomadic node models and proposed two multicast support options. The first method is a remote subscription and the second is a bi-directional tunneling [Per96a].

Another mobile node model is Mobile Ad hoc Networks (MANETs), which is an autonomous system of mobile wireless hosts. Each mobile node operates both as a host and a router. According to S. J. Lee "Ad hoc network is a dynamically re-configurable wireless network with no fixed infrastructure or central administration" [LeS00]. Various multicast routing protocols have been proposed for Ad-hoc networks. These protocols can be classified into two categories: tree-based protocols (e.g., AMRoute, AMRIS) and mesh-based protocols (e.g., ODMRP) [LeS00].

1.3.4 Mobile Satellite INTERNET

A typical geostationary satellite (GEOS) is located at an orbital altitude of 36,000 km and orbits in the equatorial plane. This orbital location results in large information propagation delays and limited coverage above ±75 degrees latitude. The communication latency between two earth stations connected by a GEOS is a considerable barrier to achieve interactive TCP/IP mechanism. Therefore, non-geostationary-orbit (e.g., Low Earth Orbit) satellite networks have been proposed as a TCP/IP compatible network solution. Low-Earth-Orbit (LEO) satellite systems operate at altitudes ranging from 700 km to 1500 km [Jam98]. This altitude results in a much

lower propagation delay compared to GEOS systems. However, a LEO satellite's footprint is much smaller than that of a GEOS. A constellation of many LEO satellites is required to cover the whole earth surface. This increases the complexity of the system relative to GEO systems.

The small footprint of LEO satellites does not usually cover all network ground stations at once. In order to exchange datagrams as well as route information via LEO satellite constellation networks, inter-satellite links are necessary [Jam98]. These Inter-Satellite Links (ISLs) are constantly changing since LEO satellite locations are not fixed. This dynamic characteristic can easily causes looping problems between nodes. That is, a packet may not reach its destination and simply be transferred among the satellites.

1.4 Scope

The scope of this research is limited to the simulation and performance evaluation of two protocols for LEO multicast satellite networks: the On Demand Multicast Routing Protocol (ODMRP) and the Distance Vector Multicast Routing Protocol (DVMRP). ODMRP is an ad-hoc network protocol. DVMRP is a nomadic host protocol. Thomas [Tho01] compared the performance of ODMRP and DVMRP under various group memberships, densities and loading levels as well as in the presence of satellite failures. This research expands upon Thomas' research. Thomas reduced the size of group membership density for the sake of simulation time, which limited its generality. This research increases group membership density. These two protocols are also subjected to more severe satellite failure conditions. Failures in multiple satellites expose how robust the protocols are to satellite failure conditions.

1.5 Approach/Methodology

When evaluating a computer system's performance, three possible methods can be used: analytical modeling, simulation, and measurement [Jai91]. Each of the above methods is considered as a possible evaluation technique to support this research. According to Jain, "Measurements are possible only if something similar to the proposed system already exists" [Jai91]. Since there does not exist a LEOS system to measure data from, this technique is not a viable option for this research

The second evaluation technique is analytical modeling. Analytical modeling techniques typically provide low accuracy because of simplifying assumptions necessary to make the mathematics tractable [Jai91]. Because of the dynamic nature of the system under test and the low level of accuracy, analytical modeling is not used for this research. Consequently, this method of evaluation is excluded.

Simulation is chosen as the technique to evaluate the performance of multicasting communications for mobile satellite networks. Simulation models relieve some of the limiting assumptions associated with analytical modeling and can produce results that more closely approximate the performance of actual systems [Jai91].

1.6 Materials and Equipment

The Optimized Network Engineering Tools (OPNET) Modeler 8.0 is used for the modeling and simulation tool for this research. OPNET Modeler has a hierarchical structure that consists of network, node, and process models. The lowest level, the process model is structured as a finite state machine (FSM) and uses C or C++ code to

supplement existing library modules. For the satellite constellation design, Satellite Tool Kit (STK) 4.0 by Analytical graphics is used. OPNET can import satellite constellation data created in STK to build a network model.

1.7 Summary

This chapter presents an overview of the research conducted. Section 1 described the research problem and summarized the current knowledge. The research scope and approach used to solve the research problem and the research tools used were described.

The remaining chapters of this thesis are laid out as follows. Chapter 2 presents a detailed background and literature review for satellite systems and multicast communications. Chapter 3 describes the methodology and simulation model developed to support this investigation. The LEOsat network performance results are presented in Chapter 4 with research conclusions and recommendations for future work presented in Chapter 5.

Chapter 2: Literature Review

2.1 Introduction

In Low-Earth-Orbit (LEO) satellite networks, the constellation can provide coverage of the whole earth. To support this "whole earth" coverage, the LEO satellite networks must have a robust routing algorithm to seamlessly route a datagram to its destination. The LEO satellite network communications are thus based on the mobile Internet Protocol (IP). This review discusses the mobile IP support for multicast communications in the satellite constellation networks. This chapter discusses IP multicasting model, routing algorithms, and protocols. The Mobile IP standard is examined, including architectural entities and the Mobile IP mechanism. These two standard models are considered as possible techniques for mobile multicasting. Current mobile IP multicasting solutions and Mobile Ad Hoc Networks (MANETs) are described in addition to some routing protocols. Finally, mobile satellite networks are discussed focusing on how information is routed via intersatellite links.

2.2 IP Multicast

Multicasting is a communication mechanism that accepts a single datagram from a source host and then delivers the datagram to a group of destination hosts. It improves unicast (point-to-point), the traditional internetworking communication method for sending a datagram from one sender to one receiver. When a unicast system sends an individual datagram for *n* recipients of a group, it sends *n* copies of the datagram using *n* connections. This approach increases the network load and unnecessarily replicates the

datagram. Multicasting, on the other hand, sends a single datagram to a multicast router that is connected to multicast destination hosts. The multicast router reproduces the datagram and distributes it to individual hosts wishing to receive the datagram [SaM00]. Multicasting provides a suitable method for large-scale software distribution, video-conferencing, or shared workspace that needs an efficient, lower network load solution [Ram00].

2.2.1 The Standard IP Multicasting model

Stephen Deering [Dee89] proposed the standard multicast model for the Internet protocol in Request for Comment (RFC) 1112. RFC 1112 specifies the host extensions needed to support multicasting aspect. The model includes

- IP-style semantics

  A source can send multicast datagrams at any time without registration and transmission schedule. IP multicast is based on User Datagram Protocol (UDP), so datagrams are delivered to the destination group with "best-effort" reliability.

- Open groups

  Sources can come from outside the group. There can be any number of sources.

- Dynamic groups

  The membership of a multicast group is dynamic: that is, any member host of a group may join or leave without registration, synchronization, or any negotiation with central group management [Tho01].

2.2.1.1 Addressing

"IP multicasting transmits an IP datagram to a 'host group,' a set of zero or more hosts" [Dee89]. This multicast transmission implies that a source node need know the multicast host group address to send datagrams, and multicast destination hosts in the group need know the host group address to subscribe to it.

Multicast host group addresses are class D IP address. A class D address has 32 bits and "1110" as its highest order bits. The remaining 28-bits are called the "multicast host group address" ranging from 224.0.0.0 to 239.255.255.255. Unlike subnetting in the unicast address, there is no structure within this address space [Mau98].

The Internet Assigned Numbers Authority (IANA) allocates some of the Class D addresses for special purposes. Multicast host group addresses ranging from 224.0.0.1 to 224.0.0.255 are reserved for exchanging routing information and other low-level topology discovery or maintenance protocols. The addresses ranging from 239.0.0.0 to 239.255.255.255 are reserved for use within private networks such as enterprise internetworks or intranets [Mau98].

2.2.1.2 IGMP

Hosts need to inform the local router that they wish to receive multicast datagrams sent to a given host group. The Internet Group Management Protocol (IGMP) provides the mechanism for IP hosts to report their host group memberships to any immediately neighboring multicast routers. Routers also use IGMP to discover which host groups have members on their attached local networks. There are two versions of IGMP: IGMPv1 as described in RFC 1112 [Dee89] and IGMPv2 as described in RFC 2236

[Fen97]. Currently, IGMPv2 is the more predominant version due to the benefits gained from lowering the leave latency [Mau98]. Most of the attributes of version 1 are included in version 2 with some enhancements.

As stated above, multicast routers use IGMP to query the hosts on the attached network to determine if they are members of a multicast group. There are two forms of a membership query: the *general query* and the *group-specific query*. The *general query* is used to learn which groups have members on an attached network. The *group-specific query* is used to learn if a particular group has any members on an attached network [Fen97]. On startup, the router with the lowest IP address is elected to transmit a *general query* to the all-systems multicast group (224.0.0.1) with a Time To Live (TTL) set to 1. The TTL setting ensures that the queries are not transmitted to other subnetworks. A host that receives an IGMP query sends a membership report to the groups which the host belongs.

Hosts do not send membership reports when leaving a group. In IGMPv1, if no report is transmitted after several queries from a group member, the router assumes there is no member node in the multicast group and stops forwarding multicast datagrams. This can result in the long latencies. In IGMPv2, on the other hand, when the last host leaves a multicast group, it sends a leave-group message to the all-routers multicast group (224.0.0.2). Using this mechanism, a router can immediately determine that there are no more hosts in the multicast group. As [Fen97] states, "When a router receives a leave group message from a host, it sends *group-specific queries*", to determine whether or not the host was the last group member.

2.2.2 Multicast Routing Algorithms

Several routing algorithms have been proposed to ensure that multicast datagrams are routed throughout internetworks. These algorithms can be used in implementing multicast routing protocols.

2.2.2.1 Reverse Path Broadcasting

Reverse Path Broadcast (RPB) was developed in the 1970s to provide a network-layer broadcast service. The RPB algorithm is the basis of Reverse Path Multicast (RPM). Using this algorithm, a router receives a datagram from a source, it examines whether the link to the source is the shortest path or not. If the incoming link is the shortest link, a router forwards the datagram on all links except the incoming link. If the datagram did not arrive on the shortest link, then the datagram is discarded.

RPB is an efficient way to deliver a multicast datagram on the shortest path from the source to the destination group. However, RPB is a broadcast delivery algorithm. Multicast group membership is not a factor when forwarding datagrams from a source.

2.2.2.2 Truncated Reverse Path Broadcasting

Truncated Reverse Path Broadcasting (TRPB) is an improvement of RPB using IGMP information. IGMP provides group membership information so the router can determine which host groups have members on their attached local subnetworks. If the subnets do not have any member hosts for a given destination group, the router does not forward the datagram to the subnets. Thus, the router can truncate the delivery path and eliminate unnecessary loads. However, TRPB reduces only unneeded datagrams on

uninterested subnets. TRPB does not consider group membership information when forwarding datagrams to downstream routers. TRPB only considers the group membership information in the subnetworks [Mau98].

2.2.2.3 Reverse Path Multicasting

Reverse Path Multicasting (RPM) is an enhancement to the RPB and TRPB algorithms. RPM sends a datagram along the shortest links from the source if the links lead to active members of the destination group. The first packet is broadcast to all multicast routers as in TRPB. When the packet reaches a multicast router with no members on local subnetworks, a prune message is generated and sent back to the source. Prune messages cascade hop-by-hop back to the source unless they meet an active multicast delivery tree. The prune messages contain an age field that is deleted periodically to remove outdated information. Therefore, broadcasting and pruning are repeated periodically. Using this age field, new members cannot be added until the next broadcasting and pruning cycle. When a member of a new group appears on a particular link, the adjacent router sends a graft message to its parent router. This process continues until the subtree has been grafted back to the active multicast delivery tree [Mau98].

The RPM process has a lack of scalability for many active members. Periodic broadcasts result in wasted bandwidth until updated prune messages are created. Additionally, every router in RPM must keep track of forwarding table entries or prune information [Mau98]. These drawbacks result in RPM scaling poorly as the number of active sources and groups increase.

2.2.2.4 Core-Based Trees

Core Based Trees (CBT) has been developed to address the limitations of RPM. Due to its use of a shared delivery tree, CBT scales better than RPM. CBT constructs a single distribution tree for each group to forward the multicast datagram of a particular group. A core router is chosen to be a center for delivering a multicast datagram to the group. All multicast datagrams are forwarded to the core router using the unicast method and are then distributed to the local router. A host that wants to join a group sends a membership report to its local router by IGMP. When a local router receives this report, it sends *Join Request* messages to the next hop on the shortest link towards the group's core router. *Join Acknowledgement* messages are then sent back to the corresponding local router by the core or an on-tree router. Upon receiving an acknowledgement, the local router can deliver datagrams to a new group membership host [Bal97].

A CBT multicast tree is maintained by each downstream router. The downstream router sends a CBT "keep-alive" message (*Echo-Request*) to its upstream router periodically. The receipt of a keep-alive message over a child interface result in an *Echo-Reply* response. If the response does not occur, the router sends a *Quit-Notification* message to its parent router, and also sends a *Flush-Tree* message over each downstream interface for the corresponding group. If the local router has no member or downstream on-tree router, the router sends a Q*uit-Notification* message to its parent router and removes the forwarding cache [Wah00].

A router using a shared CBT tree has current information for every active group (i.e., per tree) rather than information for every active (source, group) pair like RPM. This

decreases the size of multicast routing tables at the router. However, this shared multicast tree can result in the concentration of all the source's traffic on a single link [Sam00].

2.2.3 Multicast Routing Protocols

Most existing multicast protocols can be categorized into source-based and core-based multicast tree routing protocols based on tree construction [WaH00]. The following subsections discuss representative routing protocols for multicast applications.

2.2.3.1 Source-Based Multicast Tree Routing

A source-based multicast tree is rooted at a source node and connects to every destination node of the multicast group. The source node transmits a datagram to every member of the group via the links of a multicast tree. The following three protocols are examples of source-based multicast protocols:

2.2.3.1.1 Distance Vector Multicast Routing Protocol

Distance Vector Multicast Routing Protocol (DVMRP) implements the RPM protocol. DVMRP was first derived from the Routing Information Protocol (RIP) with TRPB. Based on RPM, DVMRP employs a prune message to delete the leaf network without a member host. Each DVMRP router then updates the forwarding table accordingly. The DVMRP also uses the RPM graft message to cancel the previously received prune message if a new host wants to join the leaf network. This mechanism quickly returns a formerly pruned leaf network to an active delivery tree.

DVMRP maintains a metric. The metric indicates the routing cost of the link and is used for choosing the reverse shortest path tree. For example, if a particular router's metric (router A) is less than the other router's metric (router B), router A is chosen as the dominant router and forward datagrams from the source subnetworks, while router B discards datagrams from the source. When both routers A and B have the same metric, the router with the lower IP address becomes the dominant router [Mau97].

2.2.3.1.2 Protocol Independent Multicast DM

Protocol Independent Multicast Dense Mode (PIM-DM) is also based on the RPM protocol like the DVMRP. However, there are two differences between PIM-DM and DVMRP. The first is that PIM-DM uses whatever unicast routing table is available, while DVMRP retains its own routing table (i.e., Routing Information Protocol) to check reverse path forwarding. PIM-DM simply employs the existing unicast routing table and is thus independent of any specific routing protocol. The second difference is that PIM-DM forwards multicast packets on all non-incoming interfaces unless prune messages occur. DVMRP determines the downstream routers that reach the source, therefore avoid sending unnecessary packets. PIM-DM is designed to be independent of any unicast routing protocol and avoids the complexity of using its own routing table but trades off excess datagram duplications [Mau97].

2.2.3.1.3 Multicat OSPF

Multicast Open Shortest Path First (MOSPF) is an extension to the Open Shortest Path First (OSPF) algorithm. OSPF is a unicast routing protocol that is used in

Autonomous System (AS). The OSPF keeps the topological and state information of the AS, namely the link-state database that is constructed using Link State Advertisements (LSAs). A router calculates the shortest path for any router employing LSAs.

The MOSPF adds a new OSPF LSA called the group membership LSA to maintain group membership information. A router in MOSPF distributes group membership information by flooding the group membership LSA throughout the AS. When a router receives multicast datagrams, it computes the shortest path using Dijkstra's algorithm [May94].

2.2.3.2 Core-Based Multicast Tree Routing

A tree is centered on a core router or Rendezvous Point (RP) and constructed to all the group members. All source nodes for the multicast group share this tree, while a source-based multicast tree is used for each source. In a wide area multicasting network, a core-based multicast tree offers better scalability than a source-based multicast tree [ChW98]. Two core-based multicast tree routing protocols are discussed below.

2.2.3.2.1 Protocol Independent Multicast Sparse Mode (PIM-SM)

Protocol Independent Multicast Sparse Mode (PIM-SM) uses any existing unicast routing tables like PIM-DM. Tree construction, however, is not like PIM-DM. It is based on CBT multicast algorithms. As stated above, CBT has the disadvantage of traffic concentration and a single point of failure. DVMRP employs a pruned Reverse

Shortest Path Tree (RSPT) and has the drawback that it must broadcast the first packet. PIM-SM has been proposed to overcome these shortcomings.

The router with an active group member constructs a multicast tree toward the group's RP to meet the sources. Explicit PIM-SM Join Messages, like CBT, are also sent to the RP through intermediate routers to make a forwarding state. Thus, every router knows how to route multicast datagrams to the designated RPs for a given multicast group. Unlike CBT that suffers from the limitation of a single point of failure, the RPs in PIM-SM are discovered and maintained by a bootstrap protocol [Mau97]. When a source transmits its first packet to a multicast group, the source's local router encapsulates the PIM-SM Register Messages with the data to the RP for that group. Upon receiving this message, the RP sends a PIM-SM Join Message to the source's local router. After establishing this initial forwarding state, the RP can receive regular multicast datagrams without encapsulation [Mau97].

PIM-SM can switch to the source-based Reverse Shortest Path Tree (RSPT) algorithm if a high data rate from a source occurs and exceeds a predefined threshold data rate. The source-based trees may be well suited for high data rate sources [Sam00]. A leaf router sends a PIM Join Message toward the source to create the source-based tree, while conventional source-based tree algorithms (i.e., DVMRP, PIM-DM) broadcast initial packets. When a source router receives the Join Message, the source-based tree is active.

2.2.3.2.2 Simple Multicast (SM)

Simple Multicast (SM) is similar to PIM-SM except in how it resolves the multicast address allocation problem. SM employs the identifier of a multicast group that has the 8-byte combination of a core node *C*, and the multicast address *M*. However, *M* does not have to be a unique across the Internet as in conventional IP multicast, but must be unique per *C*. Every core node *C* in the Internet can be assigned the full 28 bits multicast address. This process lessens the complexity and coordination of unique multicast addresses across the Internet [Per98].

2.3 Mobile IP

Mobile IP is designed to permit a host to change its point of attachment from one network to another while maintaining existing communications. This network may be a wireless network with limited bandwidth and higher bit error rates than wired networks. Particularly, Mobile IP provides a mechanism for routing IP datagrams to mobile hosts that may be connected to other networks while keeping their permanent IP address [Sol98]. As the Mobile IP name implies, its purpose is host mobility. The IETF Mobile IP Working Group (RFC 2002) defined Mobile IP to support a mobile routing implementation.

2.3.1 Mobile IP architectural entities

Mobile IP, RFC 2002, introduces new functional entities to support its mobility protocols. These entities are the

- Mobile node

A host or router that changes its point of attachment from one network or subnet to another. A mobile host may maintain communications at any location without changing its permanent IP address.

- Home agent

This is a router on a mobile host's home network. The home agent maintains the mobile host's current location (i.e., care-of-address) and tunnels a datagram for delivery to the mobile node.

- Foreign agent

This is a router on a mobile node's remote network. The foreign agent helps a mobile host to notify its home agent of its current care-of-address. The foreign agent detunnels and delivers datagrams to the mobile hosts that were tunneled by the mobile node's home agent. For datagram generated by a mobile host, the foreign agent may serve as a default router [Per96a].

2.3.2 IP-in-IP Tunneling

IP-in-IP tunneling was proposed to deliver IP packets to a mobile host using mobile IP. IP-in-IP tunneling implies that an IP packet is encapsulated within another IP packet and then decapsulated at an intermediate router. In the general tunneling case, two main functional nodes are necessary. These are an encapsulator node and a decapsulator node. When a packet is sent to a mobile host, an encapsulator node employed by the home agent encapsulates the original IP packet within another IP packet containing a decapsulator node address. The decapsulator node simply decapsulates the original IP packet and transmits it to its final mobile hosts using standard IP routing methods [Per96b].

2.3.3 Mobile IP overview

Mobile IP provides two main services to support a host's mobility: agent discovery, and registration [Per96a].

In agent discovery, home agent and foreign agent periodically advertise their availability on a current attached link via an *Agent Advertisement* message. A mobile host may solicit an *Agent Advertisement* message from any local agents via *Agent Solicitation* messages.

Once a mobile host receives an *Agent Advertisement* message, it may register its current location state. The location state can be either a mobile host on a home network or on a foreign network. If the mobile host is located on its home network, it operates as a non-mobile host. A mobile host returning to its home network from being registered elsewhere, deregisters with its home agent by exchanging of *Registration Request* and *Registration Reply* messages. If a mobile host is on a foreign network, it acquires a care-of-address on the foreign network. This care-of address can be either a foreign agent care-of-address or a co-located care-of-address. In the case of a foreign agent care-of address case, a mobile host sends the *Registration Request* to the foreign agent. The foreign agent examines the request and then relays it to the home agent. A *Registration Reply* is sent back to the foreign agent from the home agent after validating the *Registration Request*. Finally, the foreign agent relays a *Registration Reply* to the mobile host. In this mode, the foreign agent IP address operates as the care-of-address that is also the tunneling end point. This means the foreign agent decapsulates packets tunneled by the home agent to the mobile host's care-of-address and send them to the mobile host. This mode is preferred because many mobile hosts can use the same care-

of address and thus overcome the IPv4 address space limitation [Per96a]. In the co-located care-of address mode, the registration process is similar to the foreign agent care-of-address case except that a foreign agent in not involved. In other words, a mobile host exchanges the *Registration Request* and *Reply* directly with the home agent. In this case, the mobile host IP address works as the care-of-address and serves as the tunneling endpoint.

2.4 Mobile Multicast

Hosts in a mobile network can move arbitrarily and unpredictably. Moreover, bandwidth limitation is an important design constraint in a mobile wireless network topology. Multicasting allows for efficient use of available bandwidth in mobile wireless networks since it employs one-to-many communications instead of multiple point-to-point communications. However, the implementation of multicast services to mobile wireless networks is still a challenging problem. For instance, all existing multicast routing protocols (e.g., DVMRP, MOSPF, CBT, PIM) assume stationary multicast hosts when creating a multicast distribution tree [ChW98].

Any consideration of mobility must consider the nomadic mobile node problem [Tho01]. In this scenario, a roaming host may be connected through various means to the network other than the well-known fixed-address domain space [Cor99].

Another mobile node model is Mobile Ad hoc Networks (MANETs), an autonomous system of mobile wireless hosts. Each mobile node operates both as a host and a router. Ad hoc networks are dynamically re-configurable wireless networks that have no fixed infrastructure [Cor99].

2.4.1 Mobile IP (nomadic) Multicasting

In IP multicast, the group address and the source IP address play an important role in a packet routing. A source host must have the network ID of its IP address that is same as the network ID of the home network. That is, the source host must be connected to its home network to achieve multicasting service [Sol98]. This is a problem for mobile hosts that are connected to a foreign network. The IETF's Mobile IP introduces the method of multicast routing support for mobile hosts [Per96a]. This mechanism has been developed to provide the same connectivity for mobile hosts as when they are connected to their home network. This method supports nomadic node models and has two multicast support options. The first method is remote subscription, the second is bi-directional tunneling.

2.4.1.1 Remote Subscription

In a remote subscription, a mobile host must re-subscribe to its multicast group upon entering a new foreign network. The foreign router must act as a multicast router and be added to the multicast tree. This option assumes that at least one multicast router is present on the foreign network.

When a mobile host located at a foreign network sends a datagram, it cannot use its home network address as the source IP address. A mobile host using the Remote Subscription method uses its co-located care-of-address as the source IP address. When a mobile host wants to receive a multicast datagram, it is required to join a multicast group via IGMP host membership reports on the foreign network router. Thus, this

option assumes that at least one multicast router is available on the foreign network [Per96a].

The main advantage of this is that the multicast datagram is delivered on the shortest path. However, if a mobile host moves frequently, it must frequently switch its subscription. This tree reconstruction cost is undesirable. A multicast datagram can be lost due to a subscription set up time [ChW98].

2.4.1.2 Bi-directional Tunneling

Bi-directional tunneling is another option to provide mobile multicasting. A mobile host may join groups via bi-directional tunneling to its home agent that is assumed to be a multicast router. This means that the transmission and reception of multicast datagrams happens through the home agent.

When a mobile host wishes to receive a multicast datagram, it tunnels IGMP messages to its home agent. The home agent adds the mobile host to the multicast tree and tunnels multicast datagrams back to the mobile host. The home agent packet tunneling is based on whether the mobile host is using a foreign agent care-of-address or a co-located care-of-address. If the mobile node is using a co-located address, the home agent should tunnel the packets to this address. Otherwise, the home agent must first encapsulate the packets inside a unicast datagram, and tunnel the unicast datagram to the foreign agent. This double encapsulation allows the foreign agent to determine which mobile host should receive the datagram after decapsulated. To send a multicast datagram to a multicast group, the datagram is tunneled to its home agent. This tunneling means the multicast datagrams are encapsulated with a unicast header with the

mobile host's home address. The mobile host must use its home address as the source IP address [Per96a].

The main disadvantage of bi-directional tunneling is convergence. This means that when multiple home agents have mobile hosts belonging to the same multicast group at the same foreign network, each home agent tunnels a copy of multicast datagrams to the foreign agent. The foreign agent decapsulates and delivers multicast datagrams to the mobile hosts. The duplicated copies of the multicast datagram will arrive at the mobile hosts [ChW98].

2.4.2 Mobile Ad Hoc Network (MANET) Multicasting

Multicasting protocols used in static networks (DVMRP, MOSPF, CBT, PIM) are not adequate for ad hoc networks. "These protocols do not perform well in ad hoc networks because multicast tree structures are fragile and must be readjusted as connectivity changes" [LeS00]. Various multicast protocols are proposed for ad hoc networks. These protocols are classified into two categories: a tree-based protocol (e.g., AMRoute, AMRIS) and a mesh-based protocol (e.g., ODMRP).

2.4.2.1 Ad Hoc Multicast Routing (AMRoute)

AMRoute [BoL98] is a tree-based protocol. It employs user-multicast trees and dynamic logical cores. However, these logical cores are not a central point for the data distribution as in CBT and PIM-SM. The cores are responsible for discovering new group members, as well as creating and maintaining the multicast tree. The user-multicast tree is created by a bi-directional unicast tunneling between multicast group

members only. Additionally, the bi-directional tunnels constructed between neighbor nodes form mesh links.

These mesh links mean tree configurations need not change due to network changes. This mechanism improves AMRoute robustness. Another advantage is that processing and storage is needed only on membership nodes since non-membership nodes are strictly excluded from the user-multicast tree [BoL98].

2.4.2.2 Ad Hoc Multicast Routing Protocol Utilizing Increasing id numbers (AMRIS)

AMRIS [WuT98] constructs a shared tree using increasing node identification-numbers. Each node within a multicast session must have an assigned number, the multicast session member ID (msm-id). A shared multicast tree is rooted at a particular node called Smallest-ID node (Sid) that has the smallest msm-id.

The Sid initiates a multicast session by broadcasting a *New-Session* packet to its surrounding neighbors. All nodes receiving the *New-Session* packet then calculate their own msm-ids using hop counts from the session initiator. Each node sends a one-hop broadcast (i.e., Multicast Beacon) to update neighboring nodes. The Multicast Beacon message includes multicast state information such as msm-ids. Thus, the msm-id increases in numerical value as a function of hops from the Sid. A node can join a multicast session by sending *a Join-Req* to a potential parent node. The msm-id of the requesting node must be smaller than that of the potential parent node.

The major advantage of MRIS is that nodes can recover a broken link quickly using one multicast beacon period. Moreover, the recovery process is executed locally without central control [WuT98].

2.4.2.3 On-Demand Multicast Routing Protocol (ODMRP)

ODMRP is a mesh-based multicast routing protocol and uses "a forwarding group concept (i.e., subset of nodes forwards the multicast packets via scoped flooding) " [BaL00]. It is an on-demand procedure where routes are built on request.

If a multicast sender has a multicast packet to send, it establishes a multicast route and refreshes group membership by sending a *Join Query* message periodically. This message advertises a multicast membership. Upon receiving the *Join Query* messages, a multicast receiver generates and broadcasts a *Join Reply* to its neighbor nodes. The Receiving a *Join Reply* means a node realize whether it is on the path to the source. If it is, it will be the part of a forwarding group. Each forwarding group member propagates the *Join Reply* until it reaches the multicast source via the shortest path. This mechanism creates the path between pairs (sender, receiver) and forms a mesh of nodes (the forwarding group). The meshes of nodes overcome many drawbacks in mobile wireless networks such as intermittent connectivity and traffic concentration. [BaL00].

2.5 Mobile Satellite Internet

As wireless mobile network technologies develop, the mobility and reach of the telecommunication services are becoming independent of locations. The importance of satellite networks will increase due to the global visibility and the importance of telecommunications.

A geostationary satellite (GEOS) is located at 36,000 km altitude over the equator. This results in high-propagation delays and limited coverage above ±75 latitude degrees.

The communication latency between two earth stations connected by a GEOS is a considerable constraint achieving an interactive TCP/IP mechanism. Therefore, non-geostationary-orbit satellite networks have been proposed as a TCP/IP compatible network solution. Low Earth Orbit (LEO) satellite systems operate at altitudes ranging from 700 km to 1500 km [Jam98]. This results in a considerably lower propagation delay. However, a LEO satellite's communications footprint is much smaller than that of a GEOS. A LEO satellite does not stay in a fixed position. A constellation of many LEO satellites is required to cover the whole earth surface. This increases the complexity of the system relative to GEO systems.

The small footprint of a LEO satellite does not usually cover all ground stations at once. In order to exchange a datagram as well as route information via a LEO satellite network, establishing intersatellite links is necessary [Jam98]. Inter-Satellite Links (ISL's) are still a challenging problem and directly impacts the ad-hoc routing protocol environment [Tho01].

2.5.1 Inter-Satellite Links (ISL'S)

Since LEO satellites do not remain in a fixed location, inter-satellite links between satellites are constantly changing. This characteristic can easily causes a loop problem between nodes. In other words, a packet may not ever reach its destination and simply circulate around in the network. To solve this problem, Pratt [Pra99] researched dynamic routing algorithms in LEO satellite systems compared the Extended Bellman Ford (EXBF) and Darting algorithms.

The EXBF [ChR89] is based on the conventional Bellman-Ford (BF) algorithm and includes some enhancements to address packets circulating around the network. EXBF eliminates this issue in the BF algorithm by maintaining simple paths to a node and updating the paths to selected neighbors. This results in reducing the long convergence time [Pra99].

The Darting algorithm was developed to reduce the high overhead associated with the flooding type algorithms [TsM95]. The algorithm postpones "update" message transmission until needed. Darting uses two different mechanisms to update a routing table. One mechanism updates downstream nodes and the other updates upstream nodes. Downstream updating embeds recent local topology changes into outgoing data packets which are propagated to successor nodes. Nodes update their routing table and passes updates along the data path. If there is a discrepancy in the topology between the current nodes, an immediate predecessor node updates upstream nodes. [Pra99].

2.6 Conclusion

This chapter presents the current state of IP multicast, including address allocation and IGMP. Multicast routing protocols are classified in two categories source-based, core-based and were developed from various multicast routing algorithms. Current developments in the mobile IP were introduced. Multicast for Mobile IP discussed nomadic multicasting and MANETs. Finally, a mobile satellite Internet was examined focusing on Inter-Satellite Links.

In mobile satellite Internet, the need for robust routing algorithms increase, since the mobile node moves constantly. Additionally, multicasting is increasingly required to save limited network bandwidth in the wireless environment. Multicasting in the mobile satellite networks is an extremely challenging problem and efficient solutions are currently unknown. This research examines the efficiency of some multicast routing algorithms for a mobile satellite networks.

Chapter 3: Methodology

3.1 Introduction

This chapter presents the methodology used during this research. Section 3.2 defines system boundaries including satellite specifications, protocol selection and the scope of the system investigation. Section 3.3 presents and describes the performance metrics used to evaluate the system. Section 3.4 presents system and workload parameters. Sections 3.5 and 3.6 describe system factors that were varied in terms of users and failure satellites. In section 3.7, the experimental design is presented. Section 3.8 concludes with a description of the verification and validation techniques used to support this research.

3.2 System Boundary

3.2.1 Satellite Specifications

Previous research examined the performance of Low Earth Orbit satellite networks [Fos98, Pra99, Tho01]. These efforts chose the now bankrupt Iridium constellation as the framework for investigation. The previous efforts chose Iridium based on its uniqueness of design and also due to its applicability to military operations. This research is also based on the Iridium constellation in order to compare results with the previous work using the same conditions and assumptions.

The Iridium constellation, as proposed, consists of 66 satellites operating at an orbital altitude of 780 km. Each orbital plane contains 11 satellites in a polar orbit with an

inclination angle of 90° relative to the equatorial plane. To maintain whole-earth coverage, six orbital planes are required. Co-rotating planes are separated by 31.6 degrees and counter-rotating planes are separated 22 degrees [Rod95]. This constellation requires Inter-Satellite Links (ISLs) to transfer data. Each satellite has links to four adjacent satellites: forward-aft (in the same orbital plane), west-east (in adjacent orbital planes) [Jam98].

The footprint of satellite is critical, in terms of user number per satellite. Due to the low 780km altitude, each satellite has a relatively small coverage area. Thomas [Tho01] calculates a maximum communication coverage radius of 2436 km using Pythagorean's theorem and assumes 48 spot beams per satellite. Each spot can support 80 users [Tho01]. Section 3.5 discusses the number of users in more detail.

The data rate of the ISLs and up-down link is 2.5 gigabits per second [Tho01]. In particular, 2.5 Gbps up-down links enable multiple users to access to a single satellite.

3.2.2 Multicasting Routing Protocols

Thomas [Tho01] chose to implement the Distance Vector Multicast Routing Protocol (DVMRP) and the On Demand Multicast Routing Protocol (ODMRP) to compare the performance in this Iridium satellite constellation. DVMRP use its own routing table to build a multicast tree while ODMRP creates mesh-based multicast trees. When DVMRP builds a multicast tree, it requires less overhead than ODMRP. In terms of bandwidth usage, DVMRP has the advantage. However, ODMRP creates a more reliable multicast tree due to its mesh-based structure. Because of this mesh-based structure, ODMRP is more robust in a satellite failure environment. These two

protocols are also used in this research expanding the analysis to include more ground station users and more severe satellite failure conditions.

3.2.3 Mobile IP Boundary

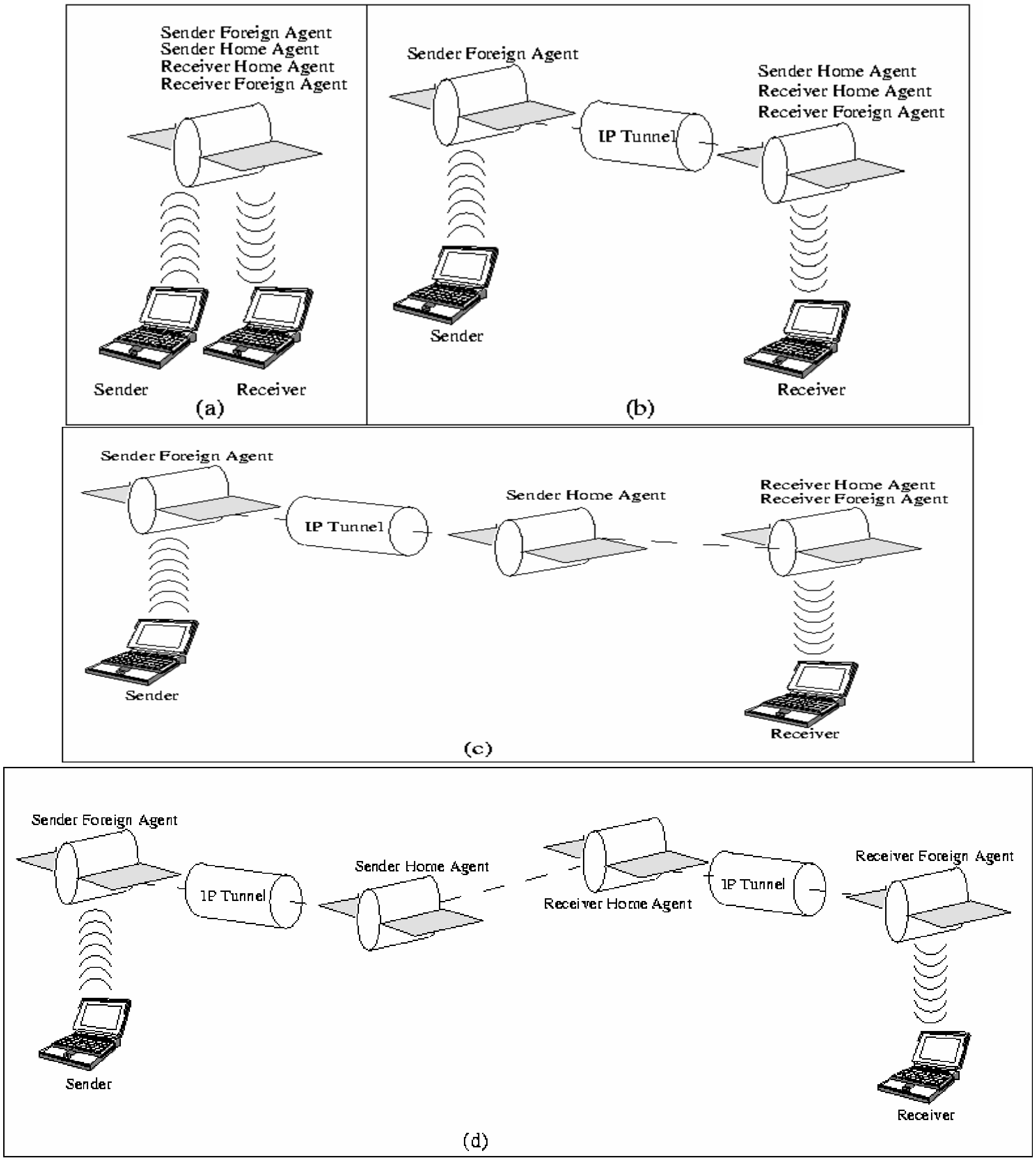


Figure 1 Sample One, Two, Three and Four Satellite Dispersal [Tho01]

Mobile IP has two multicast support options. The first is remote subscription and the second is bi-directional tunneling. These options define the relationship between a home agent and a foreign agent in support of multicasting in mobile nodes. In the Iridium satellite constellation, it is important to be able to locate the home agent and a foreign agent to support mobile nodes. Thomas designed the LEO satellite network considering possible agent locations. In his model, satellites having a routing protocol processor transfer the datagram. These datagrams originate from ground stations. Therefore, it is natural to place the foreign agent on a satellite in the ground node's view [Tho01]. The home agent thus can be placed on the ground station. According to the bi-directional tunneling method, this makes sense since the transmission and reception of multicast datagrams are controlled through the home agent. However, it is also possible to put the home agent on a satellite [Tho01]. Figure 1 shows possible arrangements of foreign agents and home agents when the home agents exist in satellites.

3.2.4 Ad hoc network Boundary

ODMRP is used as an ad hoc network protocol. A critical design issue is to the ad-hoc network boundary. Thomas [Tho01] determined that the ad hoc boundary includes both the satellite constellation and the ground stations. If the ad hoc network boundary only contains the satellite constellation, the ground stations have to register and deregister with the satellites. This registration mechanism makes ODMRP like any other routing protocol. Simply put, "Utilizing ODMRP as simply a routing protocol instead of an ad hoc manager is a waste of the overhead put into ODMRP to handle the ad hoc aspect" [Tho01]. This research follows Thomas's ad hoc boundary.

3.3 Performance metrics

The performance metrics gathered in the simulation are the *received-to-sent ratio*, *mean delay*, and the ratio of effective data bits sent on the network to overhead bits sent on the network (*data-to-overhead ratio*). These metrics come from Thomas' research to measure the same outcomes under the different scenarios.

The *received-to-sent ratio* is "The total number of packets sent by all multicast sources multiplied by the number of multicast receivers. This number is divided into the total number of packets received uniquely by all receivers" [Tho01]. This ratio shows how many packets are correctly delivered from a source to a destination (e.g., quality of service).

Mean delay indicates how long it takes to deliver datagrams through the overall network. LEO satellite systems operating at altitudes of 780 km can provide whole-earth coverage as do GEOS. Even so, propagation delay cannot be overlooked. Additionally, the mean delay is more reliable than hop count or hop ratio since the distance of inter-satellite links are not equally distributed [Tho01].

The ratio of effective data bits sent on the network to overhead bits sent on the network is another outcome. This ratio reports the number of overhead bits required to deliver the effective data bits. Data bits are defined as "bits that are successfully transmitted from source to receiver". Overhead bits are defined as "all other information transmitted over the system, including data bits that do not reach their destinations" [Tho01].

3.4 Parameters

3.4.1 Systems

3.4.1.1 Queuing model

In this satellite network model, the datagrams randomly arrive at the satellite to be serviced and the satellite uses some time to correctly deliver the datagram. The ground stations need to share the satellite routing resources since only one job can access the satellite routing service at any time. For this reason, a queuing model can be used to analyze the performance of the satellite networks.

Thomas defines this satellite network as a M/G/1 processor since it has a Poisson arrival process and the general distribution of service times. He also assumes an infinite queue length to implement the data networking rather than voice transmissions [Tho01]. According to Jain [Jai91], these conditions satisfy the M/G/1 system.

In an M/G/1 system, the datagram arrival rate, service rate, and the expected total time in the system (in queue and in service) need to be defined. The channel capacity of ISLs and up-down links were previously defined as 2.5 Gbits. This value specifies the arrival rate and the service rate under the steady-state utilization ρ. Section 3.4.2 discusses this in more detail.

The expected total time in the system (here the satellite defines the system) consists of queuing time and service time. The service time includes both transmission and processing time at each satellite. However, the processing time can be ignored because it is much smaller than the transmission time. Adding these times to the propagation

delays results in the end-to-end (ETE) delay metric. These delay times are illustrated in Figure 2

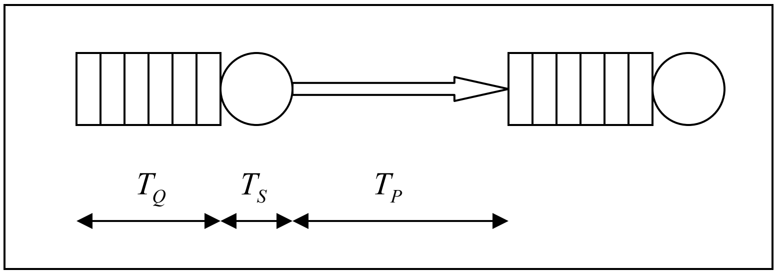


Figure 2 ETE Delay metric

where T_Q is queuing time , T_S is service time and T_P is propagation delay.

For an M/G/1 queuing model, the delay time, in terms of T_Q (queuing time), and T_S (service time) can be determining using the Pollaczek-Khinchin (P-K) formula [Jai91]. The service time, T_S , is

$$T_S = \mathrm{L} / \mathrm{C} \tag{1}$$

where L is the length of the datagram and C is the link capacity.

The queuing time is

$$T_Q = \rho E[S](1 + C_S{}^2)/2(1 - \rho) \tag{2}$$

where $E[S]$ is the expected value of T_S, ρ is $\lambda * E[S]$, λ is arrival rate, and C_S is the coefficient of variation of the service time.

Thus, the expected total time in the system becomes

$$T_{EXP} = T_S + T_Q = \mathrm{L} / \mathrm{C} + \rho E[S](1 + C_S{}^2)/2(1 - \rho). \tag{3}$$

3.4.1.2 Algorithm flow charts

Multicast algorithms for ODMRP, and DVMRP play a primary role in the entire simulation of the system. Figure 3 and Figure 4 show logic flow for each protocol algorithms implemented in the simulation.

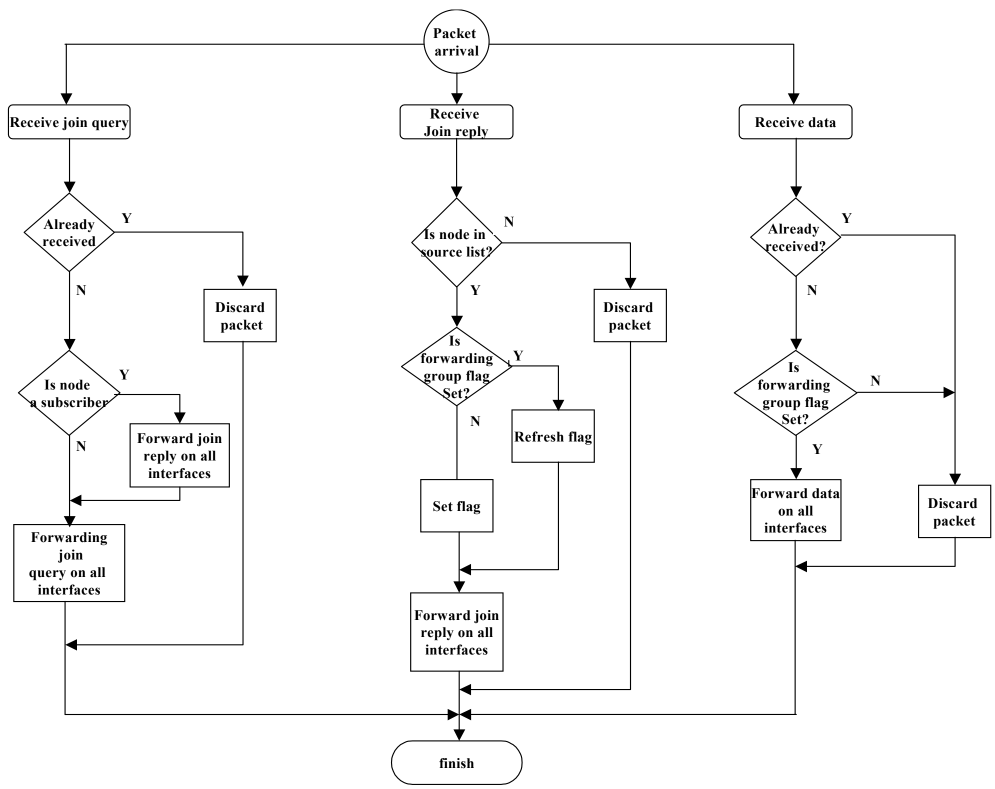


Figure 3 ODMRP Flow Chart [Tho01]

ODMRP constructs a multicast route using an on-demand procedure (i.e., *Join query* and *reply* between source and receiver). A source periodically sends a *Join query* to the

entire network to update the routes. When a multicast receiver receives the *Join query*, it sends a *Join reply* to the next node to make a forwarding group. A forwarding group flag is set if the next node is on the path to the source. Therefore, a multicast datagram can be transferred through the forwarding group.

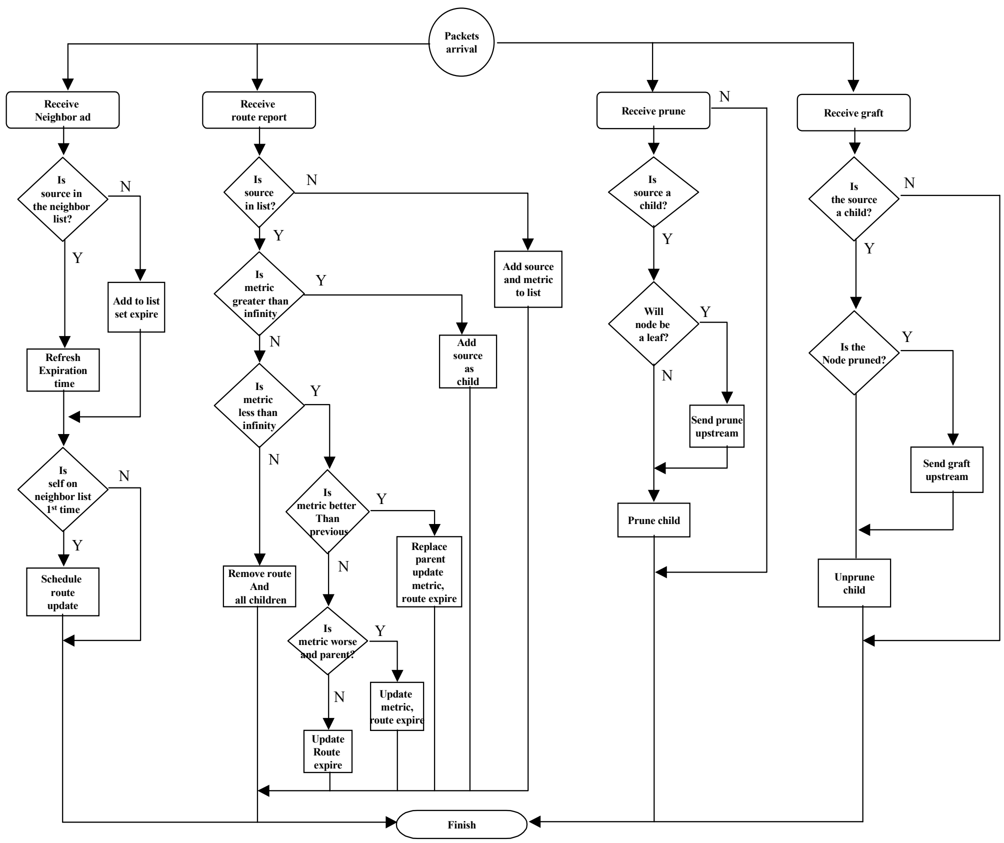


Figure 4 DVMRP Flow Chart [Tho01]

There are four possible main packet flows in DVMRP utilizing the Mobile IP mechanism. In Figure 4, leftmost column flow shows neighbor discovery advertisement between satellites. This advertisement mechanism carries out the neighbor discovery service. A route report packet creates the DVMRP multicast routing table that performs a RPF (Reverse Path Forward) check. This mechanism is based on Poison-Reverse

metrics that assign an infinite metric on an unreachable interface to determine active child interfaces. *Prune* and *Graft* packets are used to update the routes according to the multicast membership node existence

3.4.1.3 Algorithm Timing Issues

Thomas conducted pilot studies to determine the timing sensitivity of each protocol. This study limited the length of time each algorithm ran to determine its performance. Table 1 shows the timing configuration of each protocol. The timing configuration plays a system parameter role in the all simulation trials [Tho01].

Table 1 Protocol Timing Configuration

ODMRP	Forwarding Group Timeout	150sec
	Route Timeout	100sec
Mobile IP	Time Between Agent Solicitation	2.5sec
	Registration Request Timeout	5sec
	Collocated Address Timeout	10sec
	Registration Timeout	5sec
DVMRP	Neighbor Probe	26sec
	Neighbor Timeout	91sec
	Flash Update	10sec
	Prune Update	5sec
	Graft Registration	5sec
	Route Expire	140sec
	Prune Expire	600sec

3.4.2 Workload

The workload is one of the most important values affecting the throughput of the system. The packet length and arrival rate is set, so it does not exceed the predefined

link capacity 2.5 Gbps and maintains a constant utilization ρ. Thomas chose a mean data packet size of 376 bytes, and the minimum data packet size of 44 bytes. This yields the standard deviation of 375 bytes [Tho01].

The maximum service rate is the inverse of the service time T_S. The calculation for the maximum service rate is based on the link capacity 2.5 Gbps and a mean packet size of 376 bytes. Utilization, ρ, is calculated by dividing the datagram arrival rate by the system service rate. In order to reduce ρ to less than 1 so that the system is stable, the datagram arrival rate must not exceed the maximum service rate. This condition limits the loading level as shown Table 2 [Tho01].

Table 2 Loading Levels

Loading Level	Total Traffic Generation Rate
High (100%)	780 pps
Medium (80%)	624 pps
Low (50%)	390 pps

3.5 The User Number Factors

Ground stations act in a user role in this model. Ground stations generate a packet as a source and transmit the packet to the satellites. Ground stations also receive packets from the satellites. The number of users and their geographic density affects the resources required to run the simulations (to be discussed in more detail in Section 3.8). Thomas arranges user density levels into two classes: sparse and dense. Sparse mode randomly distributes the ground stations to seven urban areas as shown in Table 3. Dense mode randomly distributes the ground stations across the globe [Tho01].

Table 3 Mobile Node Home Locations

City	Longitude	Latitude	Altitude
Rio de Janero	-43.22	-22.90	0.01
Melbourine	144.97	-37.80	0.00
Kansas City	-94.59	39.13	0.23
Dharan	50.00	27.00	0.76
Beijing	116.47	39.90	0.18
Berlin	13.42	52.53	0.03
Capetown	18.37	-33.93	0.00

Thomas [Tho01] chose 5, 10, and 15 users in ODMRP and 5, 10, 15, 40, 60, and 80 users in DVMRP for group membership levels. The higher group membership levels (40, 60, 80 users) were not applied to the ODMRP scenario due to computing resource limitations. However, this research models the higher group membership levels in ODMRP scenario to compare the result with DVMRP scenario under the same conditions.

Table 4 User Factors

Density level	The number of users	Protocol	
		DVMRP/ODMRP	
Sparse / Dense Distribution	5	One-to-Many	Many-to-Many
	10	One-to-Many	Many-to-Many
	15	One-to-Many	Many-to-Many
	40	N/A	Many-to-Many
	60	N/A	Many-to-Many
	80	N/A	Many-to-Many

Two different transmission scheme scenarios, one-to-many and many-to-many are also applied to this research. Thomas' research defined these transmission schemes as "one to many (*n* members, one sender, *n* receivers) and many to many (*n* members, *n* senders, *n* receivers)" [Tho01]. Table 4 is a summary of the user factors to be evaluated.

3.6 Satellite Failure Factors

Satellite failures show the robustness of the protocol in the presence of a disabled satellite. Thomas [Tho01] induced the following satellite failure scenario:

1. Generate packet from all senders to all receivers.
2. Count packet that traverse each node.
3. Remove the satellite that has the most number of packets traversing it.
4. In case of a tie, remove the satellites with the most packets destined for Dharan

In this research, the satellite failure scenario follows Thomas' algorithms and adds more failures to satellites. For this investigation, 1, 3, 5, and 7 satellites are chosen for failure using two different strategies. The number of failed satellites follows Fossa's research [Fos98] to observe the performance under the similar failure conditions.

Satellites are chosen for failure using this algorithm.

1. Generate packets from all senders to all receivers.
2. Count the number of packets that traverse each satellite.
3. Remove the most heavily loaded satellite first then the next, and so on until you reach the 7^{th} heaviest satellite.

4. In case of a tie, remove the satellite with the most packets destined for Dharan.

This strategy is identical to Thomas' except for the increased number of failed satellites. On the other hand, the second satellite failure strategy uses a different algorithm to determine the most heavily loaded satellite.

1. Generate packets from all senders to all receivers.
2. Count the number of packets that traverse each satellite.
3. Remove the most heavily loaded satellite. In case of a tie, remove the satellite with the most packets destined for Dharan.
4. Generate packets from all senders to all receivers with **the failed satellite removed.**

Repeat steps 2 through 4 to select subsequent most heavily loaded satellites (second through seventh). Table 5 describes satellite failure factors operating under the two different strategies.

Table 5 Satellite failure factors

Factor	**DVMRP**	**ODMRP**
The number of failed satellites	1, 3, 5, 7	1, 3, 5, 7
Group membership (Sparse Mode)	5, 10, 15 users	5, 10, 15 users
Traffic Density	50%, 80%, 100%	20%, 50%, 80%, 100%
Transmission Scheme	Many-to-Many	Many-to-Many

3.7 The Design of Experiments

3.7.1 Implementation Details

The Optimized Network Engineering Tools (OPNET) Modeler 8.0 is used as the modeling and simulation tool for this research. Thomas created network, node, and process simulation models for DVMRP and ODMRP scenarios using OPNET. This research follows Thomas' network, node, and process simulation model but adds new factors to investigate the new scenarios. Table 6 summarizes every factor combination used to evaluate the simulation model

Table 6 Simulation Factors

Factors	Traffic Density	High (100%)
		Medium (80%)
		Low (50%)
	Transmission Scheme	One-to-Many
		Many-to-Many
	Group Density	Sparse
		Dense
	Satellite Failure	Failure (1,3,5,7 failed satellites)
		Non failed satellite
	Group Membership	Low membership (5,10,15 users)
		High membership (40,60,80 users)
	Algorithms	DVMRP
		ODMRP

3.7.2 OPNET process model for the protocols

The Process Model is the one of three domains in OPNET that specifies an object in the node model. The others are network and node. Thomas developed the process model that describes DVMRP and ODMRP in an event-driven simulation.

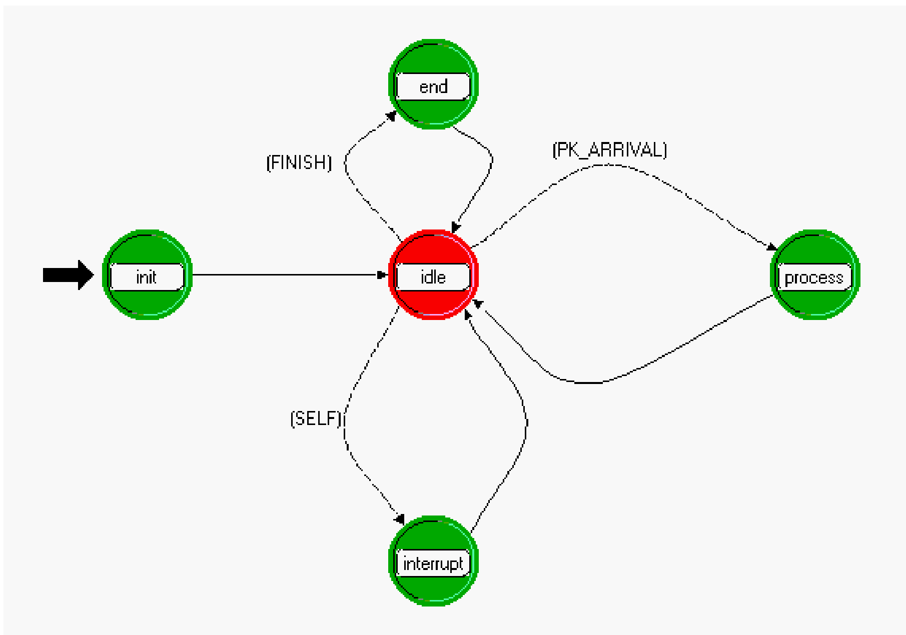


Figure 5 DVMRP Process Model

Figure 5 shows the DVMRP process model. It consists of 5 states: *init, interrupt, process, and end.* The *init* state initializes the process model and obtains the value of satellite attributes (e.g., the IP address of the satellite, DVMRP timing configurations and so on). The *interrupt* state generates self-interrupt events that occur in the DVMRP to satisfy the protocol specifications. The timing events listed in Table 1 are implemented using the *interrupt* state. The *process* state plays an important role in implementing DVMRP protocol shown in Figure 4. Route report, prune, graft, and neighbor discovery

packet arrivals invoke the *process* state. All three states transition to the *idle* state when they complete. In the idle state, the process model simply waits for an interrupt.

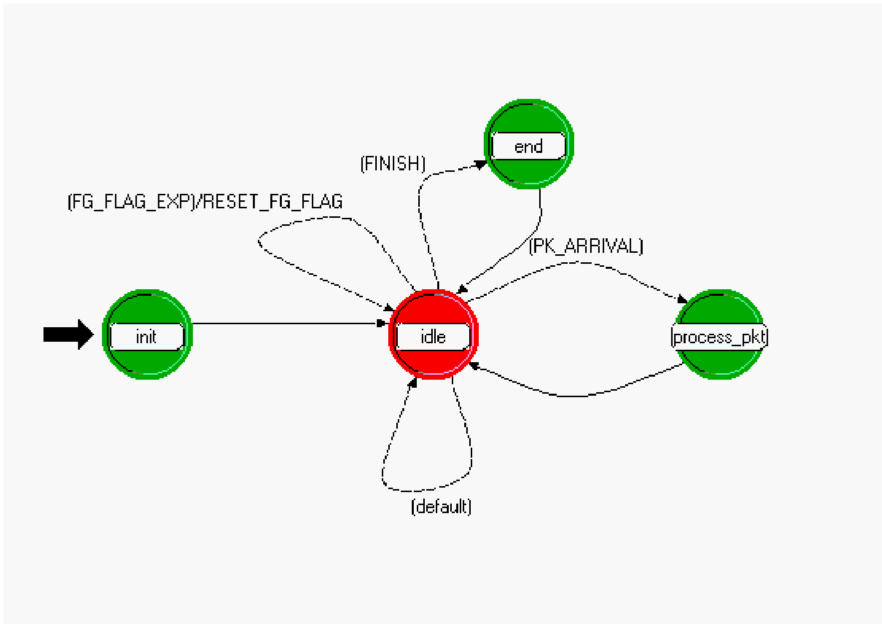


Figure 6 ODMRP Process Model

The ODMRP process model shown in Figure 6 is similar to DVMRP process model except for the interrupt state. The *process_pkt* state implements the ODMRP protocol (Figure 3) just like the DVMRP *process* state does. *Join query/reply* packet and multicast packets are processed according to the ODMRP algorithm. Forwarding group expiration is a function of the ODMRP timing. The timing is implemented using self-interrupts. If a self interrupt occurs, forwarding group is reset.

3.8 Verification and Validation

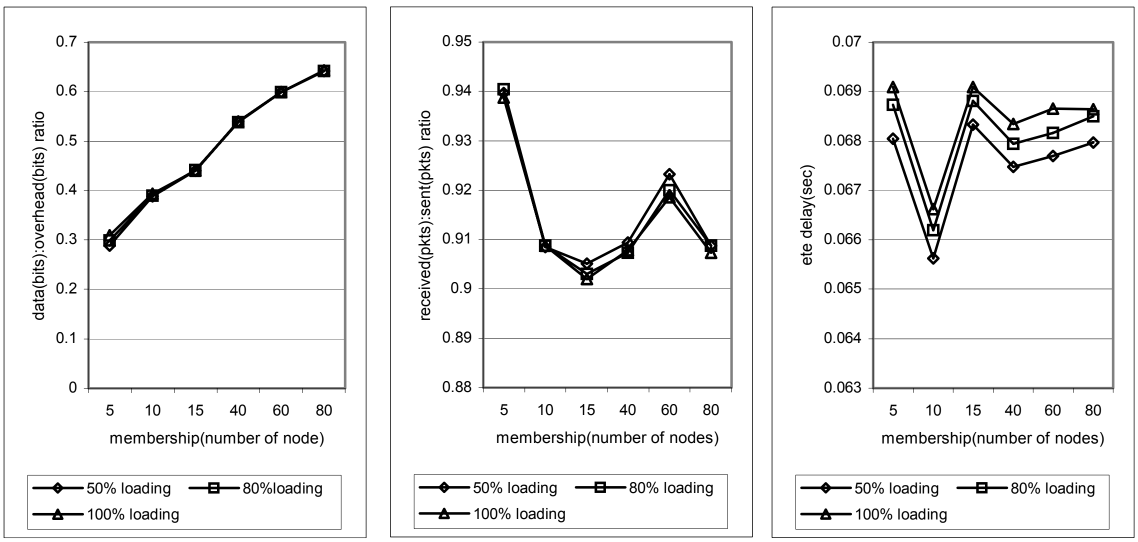
3.8.1 Verification

The model is verified using OPNET's compiler and debugger. The first verification step uses the process model compiler. The compiler checks the C++ code for errors. Next, the OPNET debugger (ODB) is used. ODB assists in resolving simulation errors (e.g., program abort, recoverable error etc.). However, even though the simulation succeeds in executing the model, the result may not be representative to the intended algorithms. In this case, the simulation is modified and iterated until the difference is found.

This research reuses the network, node, and process model used in Thomas' research. Thomas' performance results were reproduced. Figure 7 shows the DVMRP sparse (urban) distribution performance results simulated in this research as a function of loading level and number of nodes.

Plot (a) is the data to overhead ratio and increases in proportion to the number of nodes. This ratio is statistically similar across loading levels. As the number of nodes increase in sparse distribution, the co-located satellite and ground link efficiency increases because more packets are transferred through the same link. This results in an increasing data-to-overhead ratio according to the number of nodes. Plot (b) shows the received to sent ratio trends. This ratio has the highest value with 5-member nodes whose packet collision is zero, while the 15-member nodes case has the lowest ratio. In the 15-member node case, two to three ground stations stay together in a single satellite footprint which results in packet collision and lower the ratio. Plot (c) shows the end-to-

end delay increasing in proportion to loading level as expected. That is, the 100% link loading level produces longer delays than 80%, 50% loading level does. In the high membership scenario (40, 60, and 80 nodes), the end-to-end delay increases in proportion to the loading level as well as the number of nodes. As the number of nodes increase, additional traffic is generated resulting in higher ETE delays



(a) (b) (c)

Figure 7 DVMRP All-to-All Full Comparison (Sparse Distribution)

Figure 8 presents the ODMRP performance result as a function of loading level and number of nodes. This result is achieved through a many-to-many transmission scheme and sparse distribution across seven home locations.

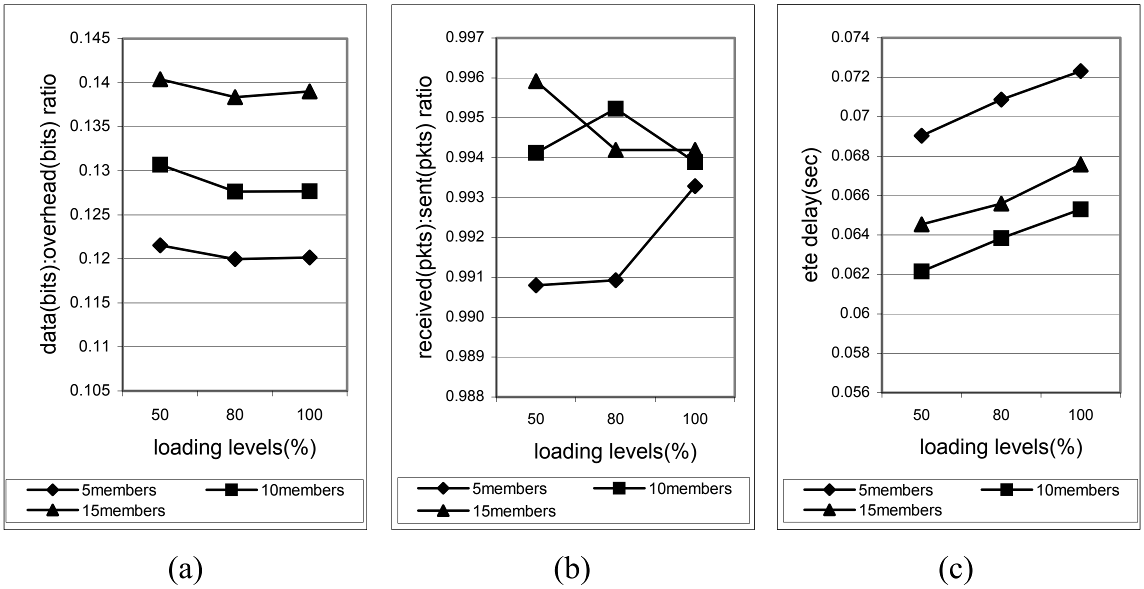


Figure 8 ODMRP All-to-all Low Membership

Plot (a) shows a data to overhead ratio whose trend is similar to DVMRP. In other words, the larger the number of nodes, the higher data to overhead ratio appears. This result is for the same reason as DVMRP, in which the co-located satellite and ground link efficiency is increasing in proportion to the number of nodes. Plot (b) is the received-to-sent ratio that shows a different trend with Thomas' results. In Thomas' results, the received-to-sent ratio converges at higher loading levels with 99.18% to 99.66% of the packet being received. Statistically, plot (b) results are equivalent to Thomas' results since the ratios are also greater than 99% with the packets being received regardless of membership and loading level. The data in Table 7 is calculated using four different random number seeds (i.e., four different samples) and 95% confidence interval. The end-to-end delay shown in plot (c) has a similar trend as DVMRP. The ratio increases proportional to the loading levels regardless of membership.

Table 7 ODMRP All-to-all Low Membership Confidence Interval

Membership	Loading level (%)	Mean	Standard deviation	Confidence Interval (95%)	
				Lower bound	Upper bound
5 nodes	50	0.9908	0.0038	0.9848	0.9968
	80	0.9909	0.0045	0.9837	0.9981
	100	0.9933	0.0007	0.9922	0.9944
10 nodes	50	0.9941	0.0019	0.9911	0.9971
	80	0.9952	0.0004	0.9946	0.9959
	100	0.9939	0.0005	0.9931	0.9947
15 nodes	50	0.9959	0.0013	0.9938	0.9981
	80	0.9942	0.0017	0.9914	0.9970
	100	0.9942	0.0007	0.9931	0.9952

3.8.2 Validation

Validating the model is a difficult problem because there is no Iridium-like satellite networks that use multicasting. However, previous research [Tho01, Pra99, Fos98] on an Iridium-like satellite network provides a good guideline to validate the model. Additionally, the simulation models used and modified in this research were already verified and validated by the previous research [Tho01].

The previous research [Tho01] did not evaluate the higher group membership levels (40, 60, and 80 users) performance in ODMRP scenario due to time and computing resource limitations. This research and previous research used Sun Ultra 10 workstations to execute the OPNET simulations. The workstation's significant features are shown in Table 8.

Table 8 Workstation Features

	Ultra 10 workstation
Processor	440-MHz UltraSPARC-Iii, 2-MB Ecache
Memory	1-GB memory, 4-GB swap memory
Performance	17.9 SPECint95, 22.7SPECfp95
Operating Environment	Solaris 8

The previous research model ran low membership (5, 10, and 15 users) level simulations without problems. However, for high membership levels (40, 60, and 80 users), a dramatic increase in the amount of computing and time resources was required. Furthermore, a memory allocation problem occurred at 60-, and 80-user levels during the simulation. The reason for the memory allocation problem was the 60, and 80-user level scenarios created an excessive amount of entities for transfer through the 66-satellite constellation. This pushed the Ultra 10 workstation resources to its limits. Table 9 shows the simulation time for high membership levels. Maximum simulation time was set to 2000 sec (33min 20sec) for a scenario.

Table 9 Simulation Time Consuming for High Membership Levels

			40 users	60 users	80 users
ODMRP	**Sparse mode**	Elapsed time	33hrs 1min	39hrs 20min	29hrs 17min
		Remaining time	0	22hrs 3min	45hrs 35min
		Simulation time	33min 20sec	23min 6sec	12min 50sec
	Dense mode	Elapsed time	36hrs 4min	40hrs 9min	29hrs 3min
		Remaining time	0	28hr	57hrs 40min
		Simulation time	33min 20sec	19min 21sec	11min 21sec

Because of memory constraints, the 60 and 80-user scenarios did not reach the specified simulation run time (2000 sec). These scenarios collect partial results that

vary the number of user and group densities. However, these results are reasonable and predictable since the simulation results trend towards steady-state rather quickly.

Figure 9 shows the steady-state trends. To verify the stability, the worst-case traffic occurrence scenarios are sampled for ODMRP. That is, the highest membership and 100% traffic loading are chosen to be the worst simulation case. These results are analyzed in more detail in Chapter 4.

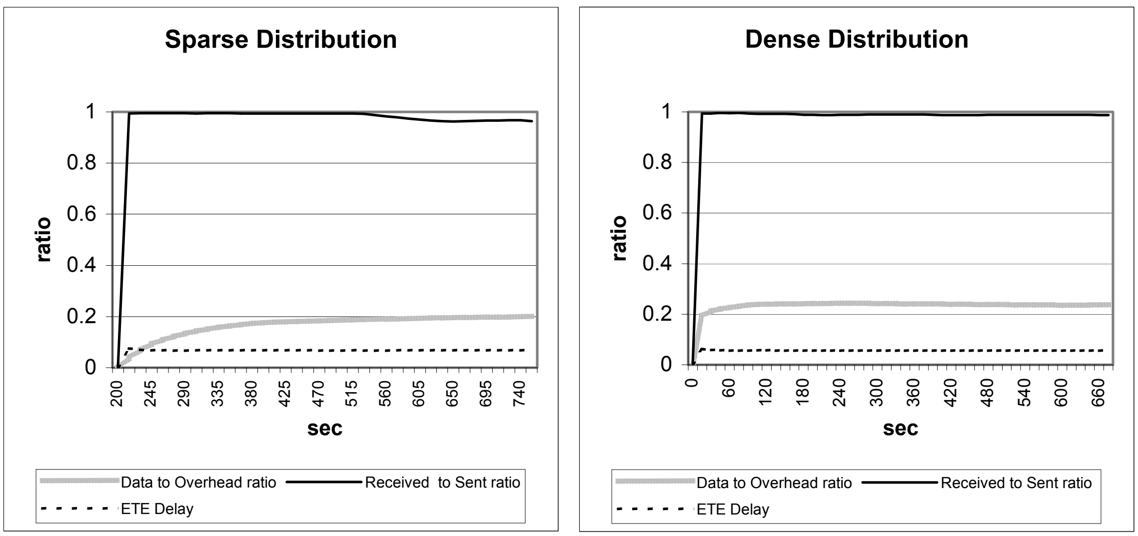


Figure 9 ODMRP High Membership (80 users)

3.9 Summary

This chapter describes the research methodology from the system boundary to detailed factors. System boundaries outlined the simulation model and limited the problem scope. Performance metrics were defined to determine system performance. Parameters and factors were presented describing the simulation model environment including satellite failure scenarios. All experimental design combinations were used to investigate the model. Finally, verification and validation technique were discussed.

Chapter 4: Results

4.1 Introduction

This chapter presents an analysis of the simulation results for each protocol. First, the statistical methods are discussed. The ODMRP simulation results for high membership scenario are analyzed in Section 4.3. Section 4.4 analyzes the satellite failure scenario of the ODMRP and DVMRP protocols. Comparisons of the two protocols are conducted in Sections 4.3 and 4.4.

4.2 Statistical Analysis

This research runs four simulations using four different random seeds to get sample performance metric results for each scenario. For instance, in the 40-users case with high traffic density (100% loading level), the ODMRP scenario has four sample results for each performance metric. The ODMRP high membership scenarios (e.g., 60, and 80 users) collect partial sample results due to computing resource constraints as discussed in Chapter 3. Eventually, these sample results allow for calculation of a sample mean ($\bar{x}$) and standard deviation (s). The 95% confidence interval of the data was calculated using

$$\left(\bar{x} - t_{[1-\alpha/2;n-1]} s / \sqrt{n},\, \bar{x} + t_{[1-\alpha/2;n-1]} s / \sqrt{n}\right) \tag{1}$$

where $\bar{x}$ is the sample mean, s is the sample standard deviation, n is the sample size, α is the significance level, and $t_{[1-\alpha/2;n-1]}$ is the $(1-\alpha/2)$-quantile of a t-variate with n-1 degrees of freedom. The 100(1-α)% confidence interval uses the (1-

$\alpha/2$)-quantile of a unit normal variate ($z_{1-\alpha/2}$) if the number of samples is greater than 30.

Sometimes, the simulation results show mean values that are similar across loading or membership levels. To investigate whether the mean values are statistically equivalent, the single-factor ANOVA (Analysis Of Variance) is used according to Devore [Dev99]. This ANOVA examines the hypothesis, H_0, that population means (μ_i) from two or more samples are equal

$$H_0 : \mu_1 = \mu_2 = \cdots = \mu_I \tag{2}$$

$$MSTr = \frac{SSTr}{I-1} \qquad MSE = \frac{SSE}{I(J-1)} \qquad f = MSTr / MSE \tag{3}$$

where $MSTr$ is the mean square for treatment, MSE is the mean square for error, SST is the sum of squares, $SSTr$ is the treatment sum of squares, SSE is the error sum of squares, I is the number of populations being compared and J is the number of samples. The calculations of SST $SSTr$ SSE are based on equation 4, 5, 6.

$$SST = \sum_{i=1}^{I}\sum_{j=1}^{J}(x_{ij} - \bar{x}..)^2 = \sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij}{}^2 - \frac{1}{IJ}x..^2 \tag{4}$$

$$SSTr = \sum_{i=1}^{I}\sum_{j=1}^{J}(x_{i\cdot} - \bar{x}..)^2 = \frac{1}{J}\sum_{i=1}^{I} x_{i\cdot}{}^2 - \frac{1}{IJ}x..^2 \tag{5}$$

$$SSE = \sum_{i=1}^{I}\sum_{j=1}^{J}(x_{ij} - \bar{x}_{i\cdot})^2 \tag{6}$$

To determine if H_0 is true or false, the F distribution is used. That is, if the computed value f is greater than or equal to the critical value $F_{\alpha,I-1,I(J-1)}$ at significance level α, H_0 is false. This case means that at least two μ_i are different,

so H_0 is rejected. The single-factor ANOVA is similar to the student *t*-test that evaluates two sample means' similarity. In other words, this technique, with $I = 2$ (the number of populations being compared), is equivalent to the student *t*-test. Therefore, the single-factor ANOVA also can investigate whether two sample means are unique.

4.3 ODMRP High Membership Scenario

In the ODMRP high membership scenario, three different numbers of user (ground stations) cases were examined in two different distribution modes. The 40-, 60- and 80-users are distributed in sparse and dense mode configurations. Sparse mode randomly distributes the ground stations to seven urban areas. Dense mode randomly distributes the ground stations across the globe. The many-to-many (*n* members, *n* senders, *n* receivers) transmission scheme was implemented so that every ground station can send and receive a packet. As discussed in Section 3.8.2, the ODMRP high-membership results converged to steady-state very quickly. Although a simulation does not reach the specified simulation run-time (2000seconds), these results are still valuable. However, few exceptions show an increasing trend. These results are also analyzed with the steady-state results in the following sections. The raw data can be found in Table 13 and Table 14 in Appendix A.

4.3.1 Data-to-Overhead Analysis

The data-to-overhead ratios shown in Figure 10 decrease slightly as the loading level increases.

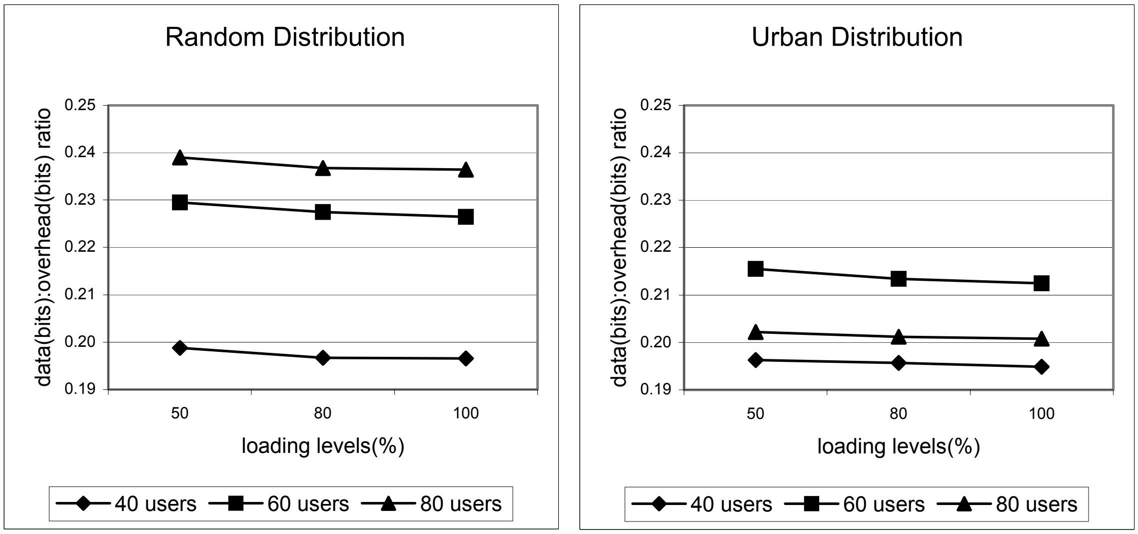


Figure 10 ODMRP Data-to-Overhead In High Membership

One of possible reason to explain this trend is packet collision at high loading level. According to Lee [LeS00], flooding packet delivery and ODMRP have a similar trend that the packet delivery ratio decreases as the loading level increases. The reason for this is that flooding and ODMRP both have a mesh structure that causes an increase in packet collisions at higher loading levels. Therefore, the packet delivery ratio will decrease at higher loading levels. The overhead includes the data bits that do not reach their destinations. Possible colliding packets increase the overhead amount, which results in lowering the data-to-overhead ratio at higher loading levels.

When users are randomly distributed across the globe, a higher data-to-overhead ratio is seen relative to the urban distribution. This trend is independent of the loading level. For instance in the 60-user case, the random distribution has the slightly higher ratio by approximately 0.014 than the 60-user case in the urban distribution. In the urban distribution, the closely co-located ground stations in the footprint of satellite access the

same link and possibly increase the packet collisions. Again, the overhead due to packet collisions decreases the data-to-overhead ratio.

4.3.2 Received-to-Sent Analysis

Trends similar to those observed in the data-to-overhead ratio are found in the received-to-sent ratio.

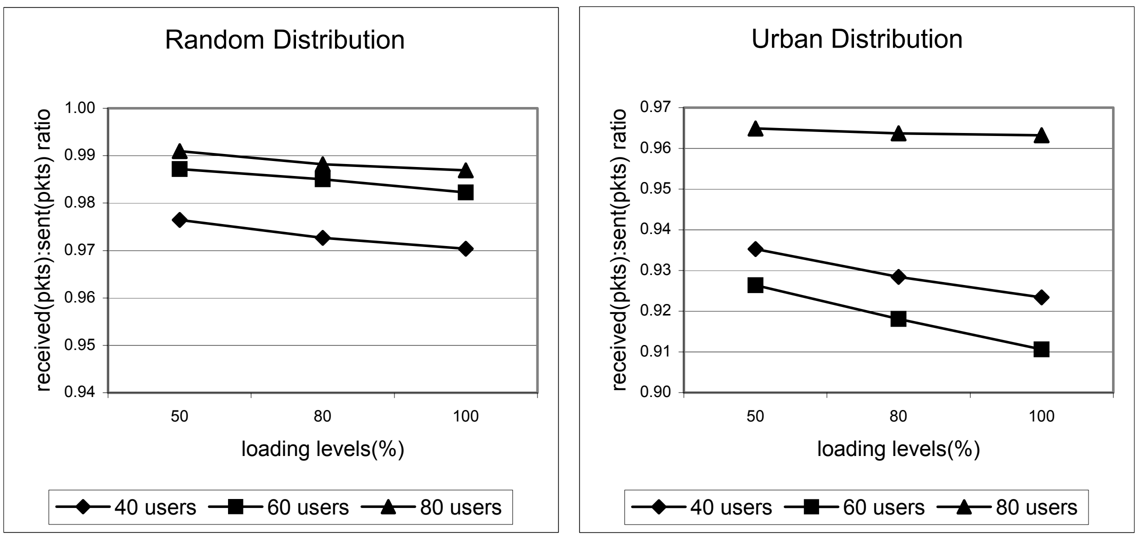


Figure 11 ODMRP Received-to-Sent In High Membership

The received-to-sent ratio is decreasing in proportion to loading level. As the loading level increases, data packet collision frequently occurs due to the nature of mesh structure. This results in the lowest ratio at 100% loading level. Another similar trend is that the ratio in random distribution is greater than the ratio of urban distribution. That is, the ODMRP protocol with random distribution of users is more reliable than the urban distribution. This result may be due to packet collisions or buffer overflow. The ground stations are grouped very tightly in urban locations. Many ground stations

access a single satellite at the same time, which may increase packet collisions and buffer overflow.

For the random distribution of user locations, the ratio is increasing as the membership is increasing. The 80-user case shows the highest reliability of packet delivery among the three user cases. The 80-users case has the largest number of nodes that can become a member of the forwarding group. Therefore, the 80-user case has the biggest forwarding group that can provide the highest packet delivery ratio. This result will be confirmed in Section 4.4.2. The higher number of ground stations case is more reliable under the satellite failure condition. However, the urban distribution result does not necessarily follow this trend. The 40 and 60-user cases do not follow the trend of increases in the received-to-sent ratio as membership is increased. These cases are unusual and the reason for this behavior has not been determined. The only modeling difference between the random and urban distributions is that the ground stations are closely co-located at one site in urban distribution and a single ground station is located at one site in for the random distribution case. This difference is probably a factor leading to the exceptional trend.

4.3.3 End-to-End Delay Analysis

The general trend of the end-to-end delay is to increase proportional to the loading level. This is attributable to the queuing delay at each satellite. Queuing delay is the only variable affecting the end-to-end delay metric since the service time and propagation delay are fixed in a given membership. The 100% loading level has the longest queuing

length and as a result, obviously, the longest delay. Figure 12 shows the effects on delay caused by increases in loading levels.

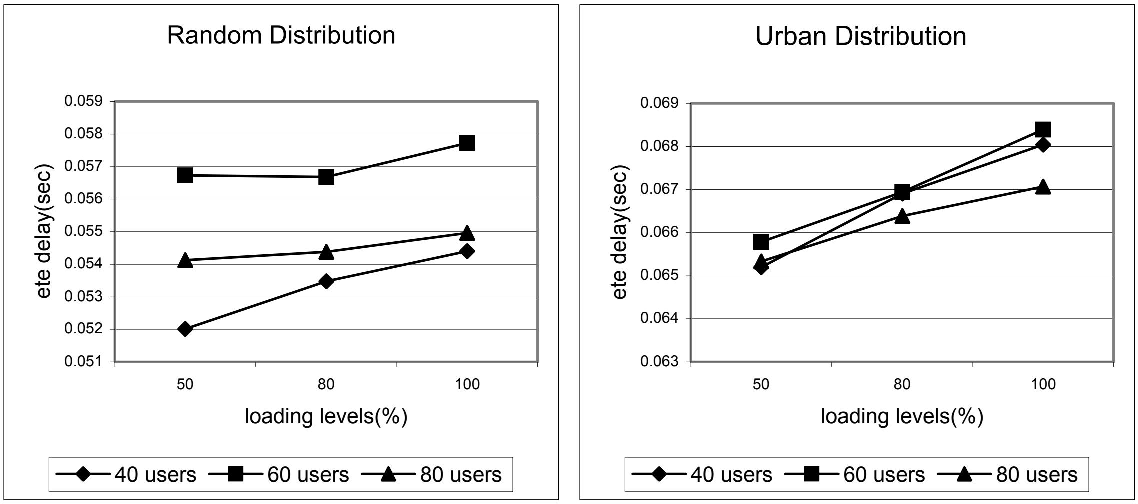


Figure 12 ODMRP End-to-End Delay In High Membership

In the urban distribution, more ground stations access a single satellite simultaneously than for the random distribution case. The satellite in the urban distribution case has a longer queuing length than the satellite in the random distribution case. This is because more ground stations share the single satellite routing resource. This results in the longer delay in the urban distribution than for the random distribution.

The 60-user case has the longest end-to-end delay in each distribution mode regardless of loading level. It is generally expected that the additional users increase the end-to-end delay due to the additional packet flow. Actually, the 80-user case in the DVMRP scenario showed the longest delay in Thomas' research [Tho01]. However, the ODMRP performance does not follow this trend. There is no conclusive evidence the delay is increasing or decreasing in proportion to the membership density.

4.3.4 The comparison of ODMRP and DVMRP in High Membership

To compare the performance between DVMRP and ODMRP for a high membership level, the random distribution mode is chosen as the point of comparison between protocols. The random distribution mode does not have the location argument shown in urban mode because a ground station is located at a single site. Figure 13 presents each performance result for the DVMRP and ODMRP high membership levels. The DVMRP performance results in high membership level are based on Thomas' research [Tho01].

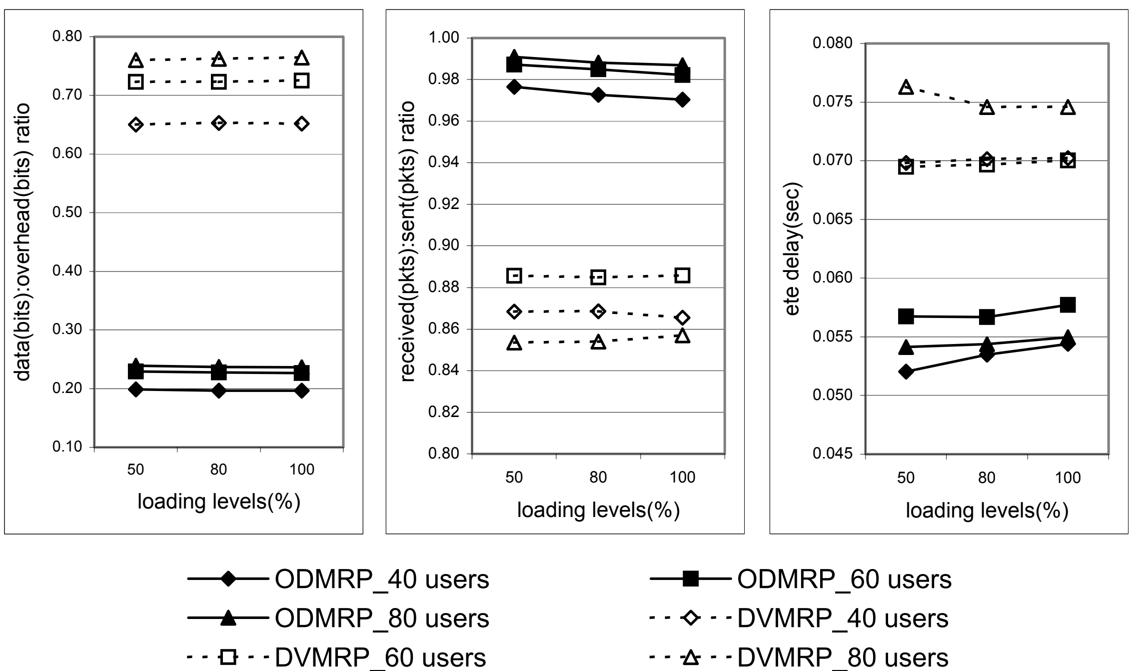


Figure 13 Comparison of High Membership Performance Metrics in Dense Mode

The data-to-overhead ratio shows the largest difference between the ODMRP and the DVMRP protocol performance. DVMRP has a much higher ratio than ODMRP. This research defines overhead as not only control packet due to the protocols but also any

data packets that fail to reach its destination as well. When ODMRP forwards a data packet, it destroys any duplicate data packets and data packets arriving to non-forwarding groups. These data packets increase the overhead in ODMRP [Tho01].

As expected, the ODMRP provides the higher received-to-sent ratio than the DVMRP. The mesh structure of the ODMRP shows higher reliability due to redundant paths. However, the typical source tree of the DVMRP shows a lower ratio. This is due to the fact that as paths change or become inoperable, data packets can be lost. The large number of ground stations in high membership level creates abundant uplinks and downlinks which increases the use of inter-satellite links. The more complicated usage of inter-satellite link may cause packet collisions, losses, and congestions to occur. ODMRP dynamically reconfigures using an alternative path while the DVMRP suffers link breaks at high membership level. The reason why the DVMRP presents the longer delay than the ODRMP is also based on this mechanism. Packet congestion results in longer delays for DVMRP, whereas ODMRP dynamically delivers a data packet using a redundant path.

4.4 Satellite Failure Scenario

Two different satellite failure strategies were used to determine protocol performance in the presence of satellite failures. After choosing the most heavily loaded satellite up to the seventh one, setting the time of the failure is needed. The failure time was considered as a parameter in Thomas' research. Thomas investigated three different failure starting times (500, 1000, and 1500 seconds) using the DVMRP protocol satellite constellation. The 500 second failure starting time was chosen because it allowed for

the greatest system performance observation time after a satellite failure. Ground stations that are in the footprint of the failed satellite cause variance in performance. The time that the ground stations are in the footprint of a failure satellite ranged from approximately 750 seconds to 1300 seconds [Tho01].

4.4.1 DVMRP Satellite Failure

The satellite constellation employing DVMRP also examined two different failure strategies to determine which strategy has the greatest impact on performance. The received-to-sent performance ratio is used to measure this impact because it represents the correctly delivered packet ratio.

Table 10 The Packet Amount in DVMRP Satellite (15 users)

Rank	Strategy 1		Strategy 2	
	Satellite Number	The number of packet (No Fail)	Satellite Number	The number of packet (1 Satellite Fail)
1	40	27585	40	Failed
2	27	26403	42	27347
3	23	26293	49	26773
4	42	26081	52	26620
5	38	25873	27	26470
6	34	25597	50	25862
7	41	25228	45	25730
8	18	25058	28	25680
9	45	24964	18	25412
10	29	24822	51	25334
11	49	24801	23	25149

Table 10 shows the number of packets traversing the most heavily loaded satellites. This data is used to determine any "hot spots" within the constellation and also indicates

which satellite should be chosen to fail. Strategy one examines the loading data on satellites in a non-failure mode and then chooses the failed satellites based on the non-failure loading. For example, satellite number 40 has the most packets traversing through it. In a single-satellite failure environment, this would be the satellite chosen to fail. Once this satellite has been caused to fail, simulations are executed again and the performance examined. Similarly for two and three satellite failures using strategy one, satellites numbered 27 and 23 would then be failed. The key aspect to remember here is that the satellites that will be chosen to fail are those most heavily loaded in a non-failure scenario. Strategy two takes a slightly different approach. Satellite number 40 is still the most heavily loaded satellite. Failure strategy two fails satellite number 40 (in a single failure scenario) and then re-executes the simulations to see how the load is redistributed to other satellites. As shown in Table 10, satellite number 42 now is the second most heavily loaded whereas in scenario one, it was the fourth most heavily loaded. This second strategy now fails these newly loaded satellites and observes the resulting performance in the multiple satellite failure environments.

Figure 14 shows that strategy one has a greater impact on performance than strategy two. The received-to-sent ratio results are shown as a function of loading level in the 5, 10, 15 user cases.

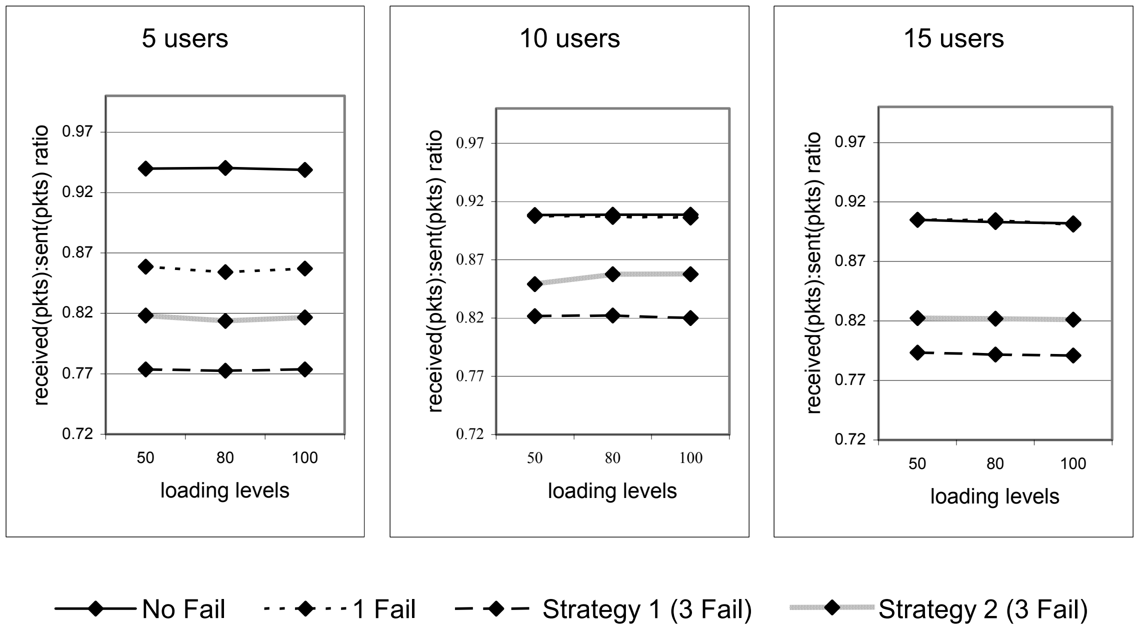


Figure 14 Effect of Failure Strategy on DVRMP

According to the DVMRP logic, the source tree is created by choosing the reverse shortest path metric to the source. That is, the heavily loaded router (i.e., satellite) has the shortest path metric to the source or the lower IP address in the case of tie metrics [Mau97]. Another possible case is that the heavily loaded router plays a common multi-access router role. Therefore, adjacent routers share this router to receive the packets. The three-satellite combination of 40, 27, and 23 has the largest number of packets transmitted from the source in the strategy one scenario. These satellites are chosen as the shortest path to the source and play a critical role in forwarding multicast packets. When strategy one is applied at the 500 seconds failure-starting time, these three satellites are in the critical path to the source. This three-satellite failure case allows 77.4% of the packets sent to be received at 100% loading in the 5-user case. This is 4.3% less than the three-satellite failure case using strategy two. In strategy two, satellites 42, and 49

show the largest number of packets, which means these two satellites are adjusted to the shortest path to the source after failing satellite number 40. However, for the three-satellite failure case (i.e., satellite 40, 42, and 49 fail simultaneously) starts to fail in strategy two, satellites 42, and 49 are not the second and third shortest path to the source as expected. In other words, this case fails satellites 42, and 49 that mark the fourth and eleventh heavily loaded satellites in strategy one before satellites 42, and 49 are adjusted to the second and third shortest path to the source. This result shows that DVRMP does not dynamically reroute the data packets as connectivity changes. Therefore, strategy two for the three-satellite failure case has slightly less impact than strategy one. The following section presents each performance metric results by applying strategy one failure scenario. The raw data can be found in Table 16, Table 17, and Table 18 in Appendix A.

4.4.1.1 Data-to-Overhead Ratio Analysis

Figure 15 presents the data-to-overhead ratio as a function of loading levels and the number of satellite failures. The general trend of the data-to-overhead ratio is increasing in proportion to the number of users. The highest ratio is for the 15 users, 100% loading level, 7-satellite failure case, which transmitted a mean of 0.448 bits of data for every one bit of overhead. The lowest ratio is the 5 users, 50% loading level, 1-satellite failure case, with a mean of 0.279 bits of data for every one bit of overhead.

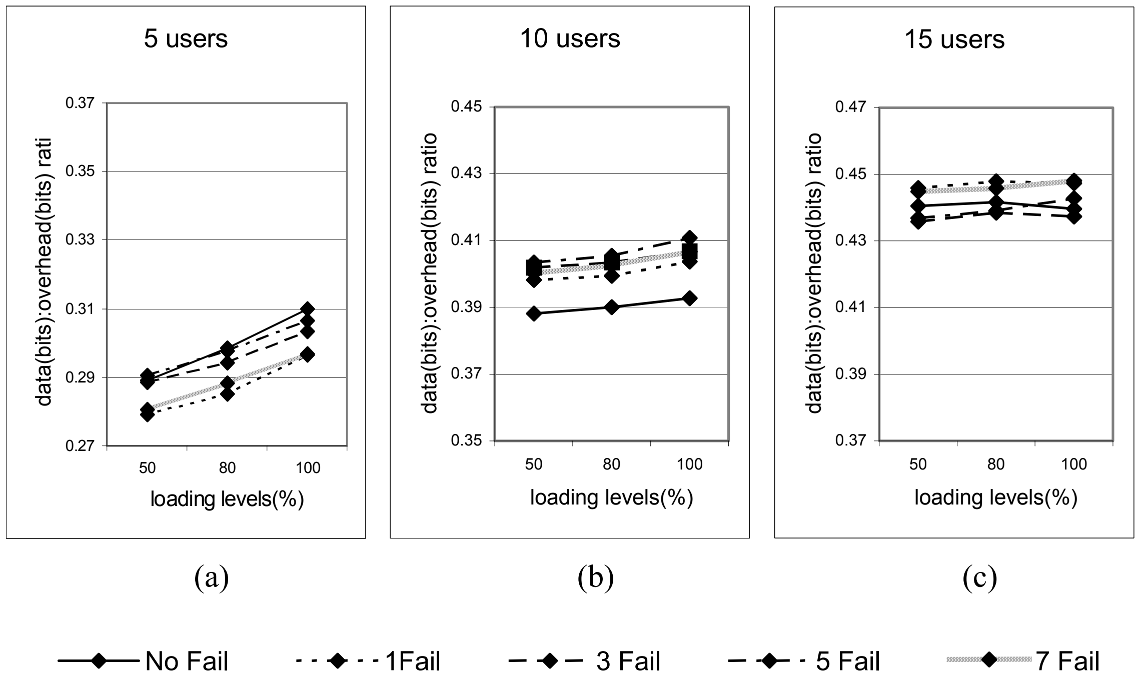


Figure 15 DVMRP Data-to-Overhead In Satellite Failures

In Figure 15.a, the data-to-overhead ratio is increasing in proportion to the loading levels. The 100% loading level in each failure case shows the highest ratio. As the loading level increases, the link utilization goes higher. Additionally, this overhead in DVMRP is independent of the transmitted data bit, which means the overhead has a relatively constant value [Tho01]. A single-factor ANOVA reveals the statistical significance. The non-satellite failure, three and five-satellite failure results are statistically identical at any chosen loading level (at significance level of 0.05). The one satellite failure and seven-satellite failure results are also statistically identical at a given loading level (at significance level of 0.05). When comparing the failure case against the non-failure case, the one and seven-satellite failure cases affect the network by a decrease of approximately 4% in the data-to-overhead ratio. This result shows that the

number of failure satellites (i.e., worst case of seven failures) is not closely related to the reduction in the data-to-overhead ratio of DVMRP.

Figure 15.b shows that the data-to-overhead ratio is slightly increasing in proportion to the loading levels like the 5-user case. However, every satellite failure case increases the ratio compared to the non-failure case in contrast to the 5-user results. The highest ratio occurs at a 100% loading level, 5-satellite failure case. In this scenario, a mean of 0.411 bits of data was transmitted for every one bit of overhead. Again, three and seven satellite failure scenario results are statistically identical at a given loading level (at significance level of 0.05) by applying the single-factor ANOVA. Comparisons of the data-to-overhead ratio fluctuations in the failed cases with the non-fail cases are unpredictable. However, this phenomenon is likely attributable to the sparse distribution of ground station (users) across the seven global locations. The 5-user case has ground stations at five sites. The 10-user case has two ground stations at three sites and one ground station at four sites. This difference causes the different phenomenon between 5-user and 10-user cases.

In Figure 15.c, the data-to-overhead ratio is not necessarily increasing in proportion to the loading level. The ratio values are statistically identical within a given satellite failure case except for the five and seven-satellite failure cases indicating the slightly increasing ratio. This trend also comes from the ground station distribution. The 15-user case has two ground stations at six sites and three ground stations at one site. The site in 15-user case has at least two ground stations at a site, which contribute to the high link utilization by sharing the same link. However, misrouted data packets also occur more frequently. Misrouted data packets also increase overhead because the overhead

includes misrouted data packet as the part of it [Tho01]. In high membership level cases (e.g., 40, 60, and 80 users) in Thomas' research, the variance of data-to-overhead ratio is insignificant across the loading level. The non-satellite failure, three and five satellite failure results are statistically identical at any loading level. The one and seven satellite failure results are also statistically identical at a given loading level. When comparing the failure cases against the non-failure case, only the one and seven satellite failure case results (80% and 100% loading level) affect the network by an approximate increase of 1.5%.

4.4.1.2 Received-to-Sent Ratio Analysis

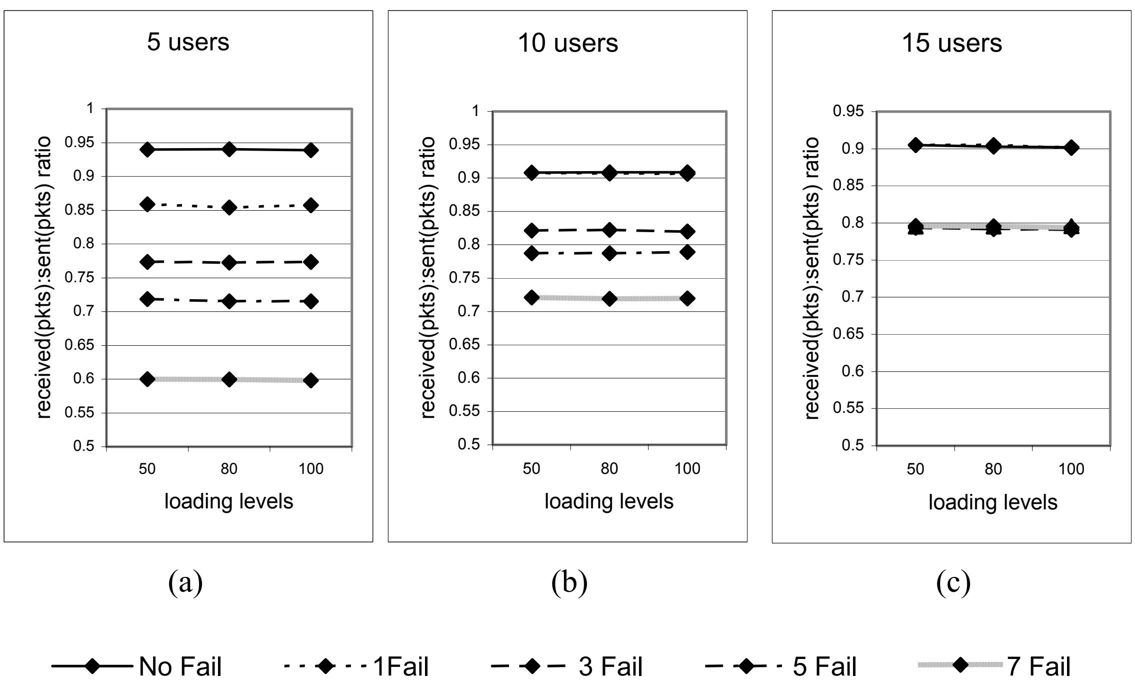


Figure 16 DVMRP Received-to-Sent In Satellite Failures

Figure 16 presents the received-to-sent ratio as a function of loading levels and the number of satellite failures. The trend of ratio values indicates a horizontal line across

the loading levels. In other words, these ratios are not different within a given satellite failure case regardless of the loading levels. However, the received-to-sent ratio is decreasing in proportion to the number of satellite failures because the packets sent from the ground stations are lost. Clearly, when the ground stations are in the footprint of the failed satellite, the failed satellite cannot receive the packets sent from the ground stations. As the number of satellite failures increase, so does the likelihood of packet losses due to ground stations not being covered by a satellite.

The decreasing trend of the ratio is different among the 5, 10, and 15-user cases. In the 5-user case, the ratio drops significantly as the number of failure satellites increases. The lowest ratio marks around 0.6 at the 7-satellite failure case. This provides a 36% difference with respect to the non-failure case. However, changes in performance of the 10-user and 15-user are not as dramatic. The lowest ratio for the 10-user case is 0.72, or a 21% decrease from the non-failure case. Additionally, the non-failure case is statistically identical to the one-satellite failure case. The 15-user case has the 12.3% difference between the failure and non-failure cases and the lowest ratio of 0.79. The three, five, and seven-satellite failure cases are statistically identical. Again, the non-failure and the one-satellite failure cases are statistically identical in 15-user scenario. The reason for this result is also based on the uneven distribution among the seven geographic locations. Table 11 presents the received-to-sent ratio calculations to explain the results given the following assumptions:

1. A ground station can send only one packet.
2. When the satellite failure occurs, it affects 5, 10, or 15 ground stations.

3. The only one of seven geographic locations is in the footprint of failed satellite. In the 5-user case, only one of five locations is in the footprint of failed satellite.

Table 11 Sample DVMRP Received-to-sent ratio calculation

The number of users	The number of sent packet	The number of received packets	Received-to-Sent Ratio	The probability of occurrence
5 users	5	4	80%(= 4/5)	100%
10 users	10	9	90%(= 9/10)	57%(= 4/7)
		8	80%(= 8/10)	43%(= 3/7)
15 users	15	13	87%(= 13/15)	86%(= 6/7)
		12	80%(= 12/15)	14%(= 1/7)

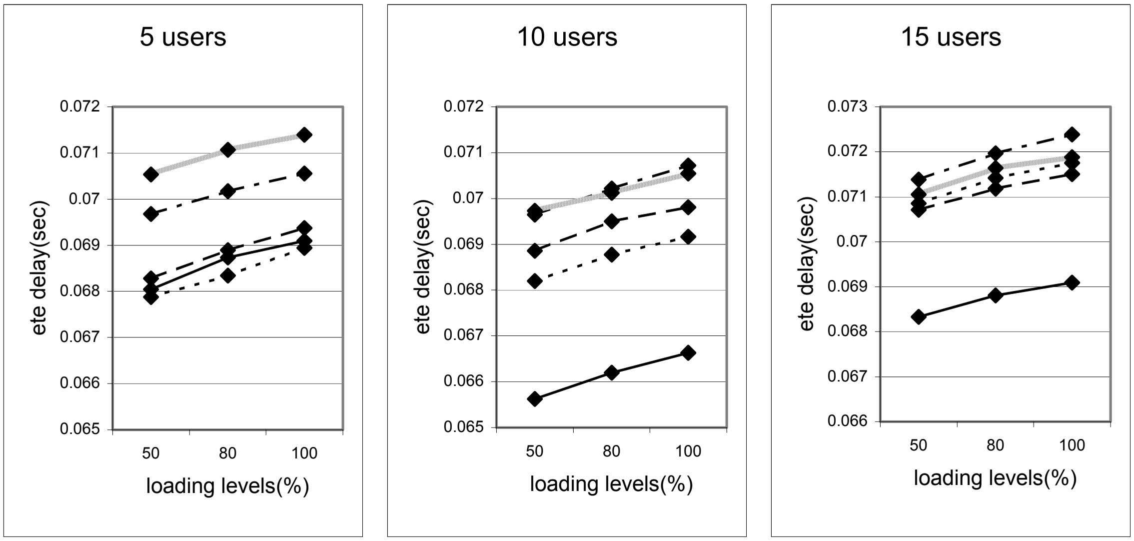
The 5-user case has the lowest received-to-sent ratio because one of five packets sent is always lost. The 10-user case has the ratio range from 0.8 to 0.9. The case where the ratio is 0.9 (one ground station per location is in the footprint of the failed satellite) happens with 57% probability. The other case (0.8 ratio) that two ground stations are in a location has 43% satellite failure occurrence probability. In the 15-user case, two ground stations are at six locations and have the highest probability of being in the footprint of a failed satellite (86% probability). This results in a little higher ratio than 10-user case.

4.4.1.3 End-to-End Delay Analysis

Figure 17 presents the end-to-end delay as a function of loading levels and the number of satellite failures.

The first trend of the end-to-end delay is increasing as the loading level increases. This trend is attributable to the queuing delay. In this research, queuing delay heavily depends on the loading level because the channel capacity of Inter-Satellite Links (ISLs)

has a fixed value (2.5Gps). The 100% loading level has the longest queuing length, which makes the delay longer than any other loading level queue.



(a) (b) (c)

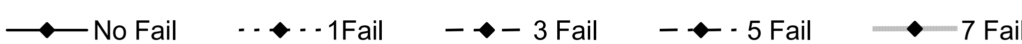


Figure 17 DVMRP End-to-End Delay In Satellite Failures

The second trend is that the delay is increasing in proportion to the number of satellite failures. This is because as more satellites fail, more packet routing is required to move the packets around the failed satellites. However, some failure cases are statistically similar in spite of increasing the number of failed satellites. In the 5-user case, the performance for the non-failure, one, and three satellite failure scenarios are statistically identical at any chosen loading level (at significance level 0.5). In the 10-user case, the five and seven satellite failure results are also statistically identical. In these cases, network performance is not affected by increasing the number of failure satellites. Unlike the five and ten user cases, the 15-user case shows that the delay does not necessarily increase in proportion to the number of satellite failures. The single satellite

failure scenario is statistically identical at significance level 0.05 to the three-satellite failure case. The seven-satellite failure case delay is greater than the single satellite failure case and smaller than the five-satellite failure case. The five-satellite failure case has a slightly longer delay than any other case. This is an unusual result. There is no conclusive evidence to explain the results.

4.4.2 ODMRP Satellite Failure

Similar to the strategy performed for the DVMRP satellite failure scenario, pilot tests were conducted under two different failure strategies to find which strategy impacts performance the most. The received-to-sent ratio performance metric was used to measure the impact.

Table 12 The Packet Amount in ODMRP Satellite (10 users)

Rank	Strategy 1		Strategy 2	
	Satellite Number	The number of packet (No Fail)	Satellite Number	The number of packet (1 Satellite Fail)
1	40	19912	40	Failed
2	29	19900	50	19997
3	50	19888	24	19968
4	34	19886	23	19964
5	23	19876	11	19956
6	11	19862	39	19853
7	39	19477	29	19838
8	17	19461	51	19829
21	24	18987	21	19346

Table 12 presents the number of packet at each satellite by applying strategies one and two in the 10-user case. In strategy one, failing satellite number 40 is the single-

satellite failure case. Failing satellites 29 and 50 along with 40 is the three-satellite failure case. For strategy two, satellites 50 and 24 are as the second and third heaviest loaded satellites. These satellites are the other two satellites in the three-satellite failure case. In contrast to the DVMRP satellite scenario, strategy two has a more impact than strategy one.

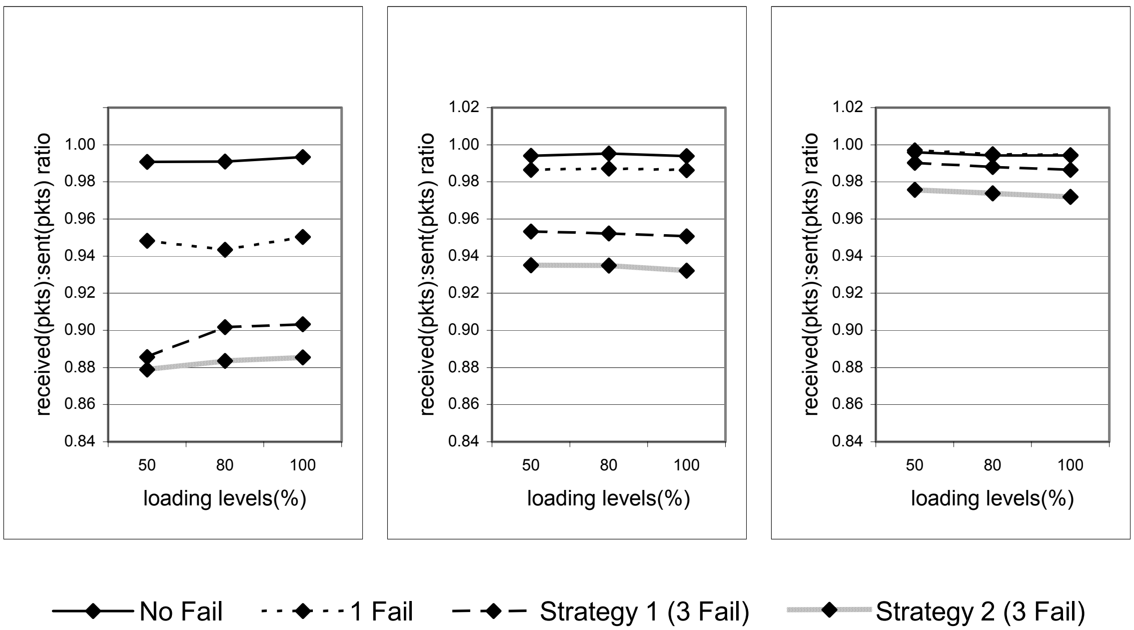


Figure 18 Effect of Failure Strategy on ODMRP

In ODMRP, the forwarding group is responsible for forwarding data packets between a source and a receiver. The forwarding group can create multiple routes because it consists of multiple nodes. It is a mesh of nodes rather than a typical tree structure. When a primary path is broken between a source and receiver, the forwarding group can provide an alternative path since it has a redundant path built by a mesh structure [BaL00]. In strategy two, the satellites numbered 50 and 24 are used as the alternative path node when the most heavily loaded satellite (number 40) fails. Satellite 24 was the

twenty-first most heavily loaded satellite in strategy one in now the third heaviest loaded satellite in strategy two. In the three-satellite failure case, packets that are supposed to be delivered to the satellite 40 are rerouted to the other failed satellites (i.e., satellites 50, and 24). This results in more packet losses than strategy one and lowers the received-to-sent ratio. This result shows that the ODRMP can dynamically reroute the packet using the redundant paths rather than readjusting the route and minimize the packet loss. The following section presents performance metric results using strategy two. To examine in more detail the relationship between the loading levels, the 20% loading level is added. The raw data can be found in Table 20,Table 21, and Table 22 in Appendix A.

4.4.2.1 Data-to-Overhead Ratio Analysis

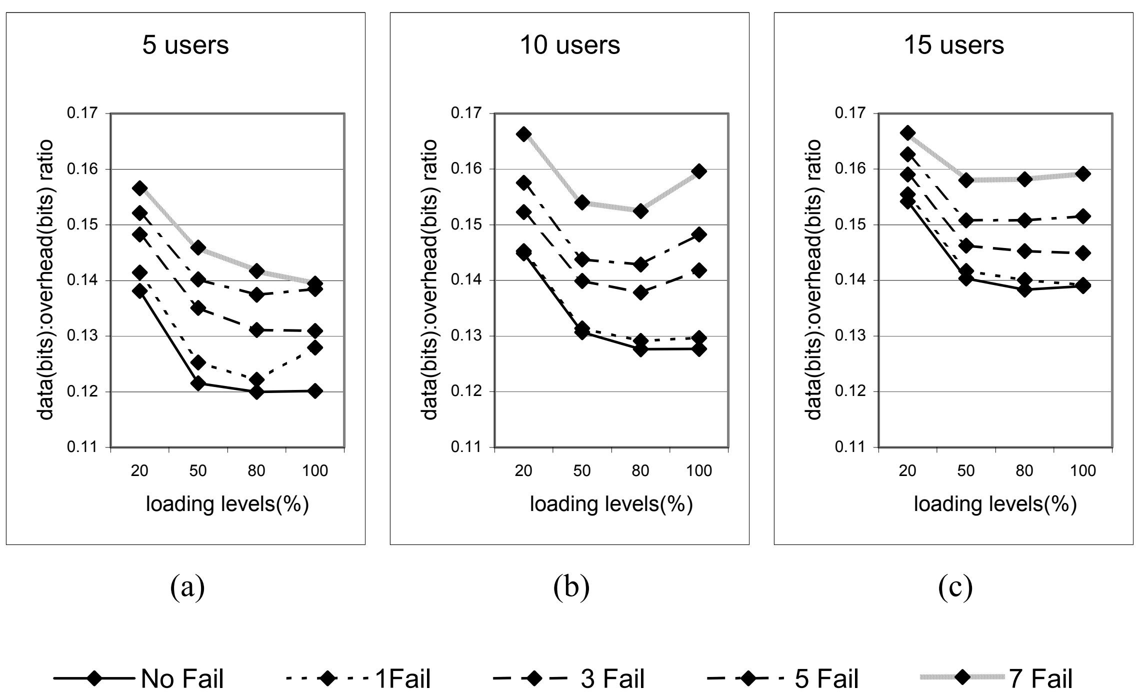


Figure 19 ODMRP Data-to-Overhead In Satellite Failures

The general trend of the data-to-overhead ratio is an increase in proportion to the number of satellite failures. The seven-satellite failure case shows the highest ratio in each case. When a satellite fails to serve as a router role, a data packet can take an alternative path. The same number of data packets is still delivered to a destination. While the data packets are rerouted, overhead packets (e.g., *Join query and reply*) used to create the mesh structure remain unchanged until updating is done by *Join query*. When ODMRP updates the route state, it broadcasts a *Join Query* to the entire network. The receiver that received the *Join Query* starts to create a forwarding group by propagating a *Join Reply* to an available node. In the satellite failure case, the failed satellite that was the member of forwarding group in the non-failure case becomes an invalid node. This causes a fewer number of control packets to be broadcast to the network. Therefore, the smaller forwarding group is created as the number of failed satellites is increasing. This results in a slightly increasing trend in the data-to-overhead ratio.

4.4.2.2 Received-to-Sent Ratio Analysis

The received-to-sent ratio in Figure 20 shows a similar trend to DVMRP. This ratio also decreases in proportion to the number of satellite failures. When a ground station is in the footprint of failed satellites, obviously, packets sent from the ground stations cannot reach a satellite. Packet losses occur more frequently as the number of failed satellites increases

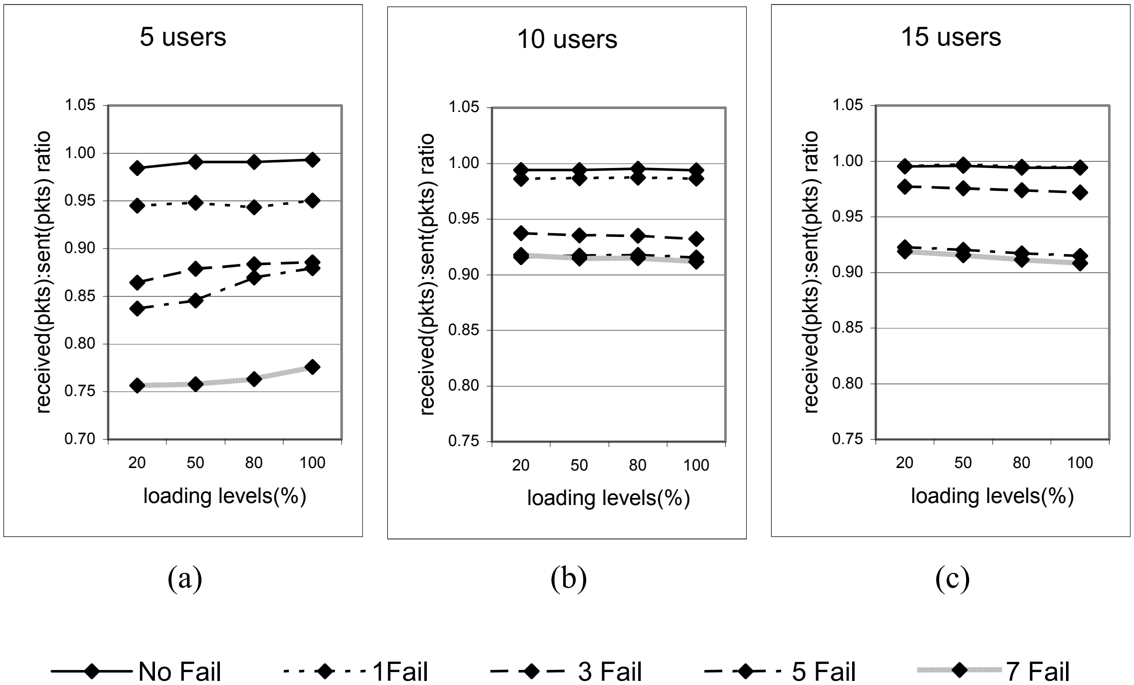


Figure 20 ODMRP Received-to-Sent In Satellite Failures

This decreasing trend varies across the different user cases. The 5-user case shows the lowest ratio for the seven-satellite failure scenario. This ratio is 0.756. However, the 10 and 15-user cases still have greater than a 0.9 ratio although seven satellites have failed. This is caused by differences in the number of forwarding groups. This research sets the ODMRP boundary to include the satellite constellation and the ground stations. This boundary can have ground stations as the part of forwarding group members that usually consist of satellite nodes. Therefore, the 10 and 15-user cases have larger forwarding group members than the 5-user case. Larger forwarding groups can create more redundant paths that ensure packet delivery with minimum packet loss. The largest forwarding group (i.e., the 15-user case) shows the robust packet delivery in

Figure 20.c. In this case, a single satellite failure does not affect the non-satellite failure case. These cases are statistically identical at significance level of 0.05

4.4.2.3 End-to-End Delay Analysis

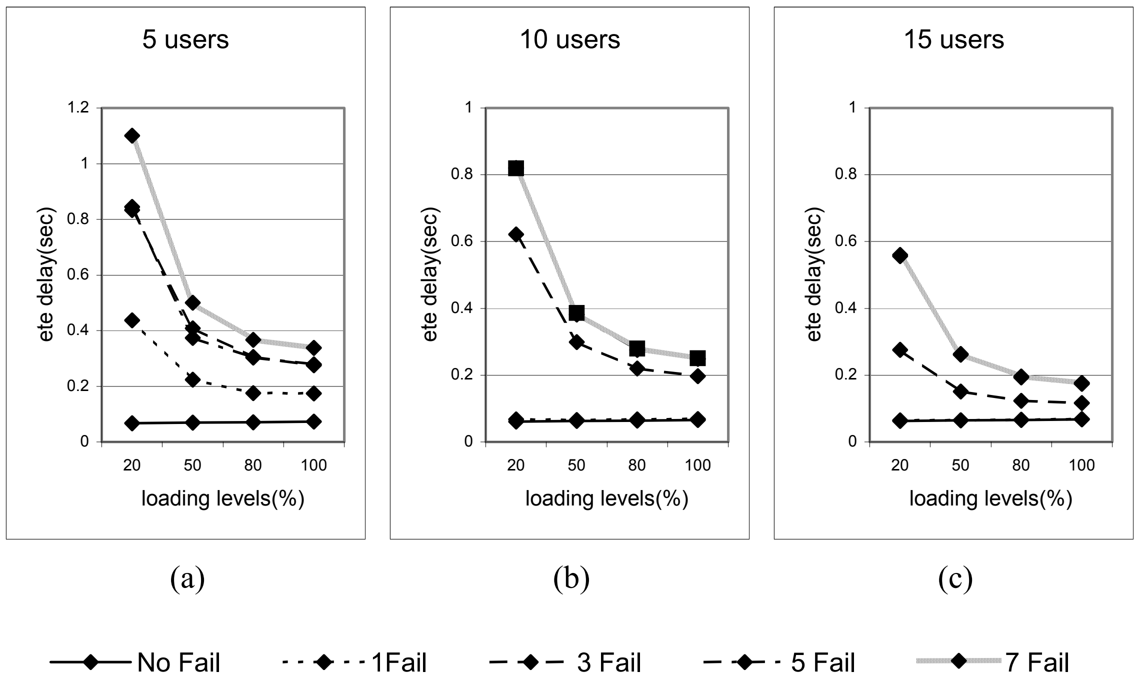


Figure 21 ODMRP End-to-End Delay In Satellite failures

The general trend of the end-to-end delay in the ODMRP failure scenario shows a larger delay as the number of satellite failures increase. The data packets are rerouted around broken paths using redundant paths created by the ODMRP. As the number of failed satellites increase, more packets are more frequently rerouted creating longer delays. However, some cases do not show this dramatic effect by simply increasing the number of failed satellites. For instance, the five and seven-satellite failure cases in the 10-user case are statistically identical at a significance level of 0.05. The statistical similarity is also observed between the five and seven-satellite failure cases in the 15-user

case. In particular, the single satellite case does not significantly affect the non-failure scenario for the 15-user case. Figure 21.c shows the almost overlapping line between the non-failure and single satellite failure scenarios. This is also attributable to the redundant paths. The 15-user case has the largest number of redundant paths among three user cases that provides robustness against the satellite failures.

In the non-failure scenario for each user level, the delay increases slightly as the loading level increases. Delay typically increases in proportion to the loading level. The 100% loading level has the longer queuing delay than any other loading level. However, the trend reverses when a satellite does not act in a node role. For instance, the three, five, and seven-satellite failure scenarios show the delay increasing as the loading level decreases in every case. According to ODMRP protocol, ODMRP updates membership and route information by sending *Join Query* control packet to the network. This *Join Query* control packet is periodically flooded only if a sender has a data packet to send. Therefore, the 100% loading level floods control packets more frequently than any other loading level. This results in updating the route information more frequently and removing the stale routes created by the satellite failures. Initially, the satellite chosen to fail was a valid node because the failure scenario begins at 500 seconds of simulation time. The 100% loading level case updates the failed satellite information faster than any other loading level by sending the control packets out more frequently. The 20% loading level may use the failed satellite as a valid satellite node before realizing it became an invalid satellite. This is because of the lack of immediate feedback through the network of satellite failures (not uncommon in an actual network). The data packet may not reach a destination and circulate around the network.

Additionally, the ODMRP has a *soft-state* to maintain the multicast group. In other words, there is no explicit message when a node member leaves or joins the multicast group. The route refreshing time (100 seconds) and forwarding group time out (150 seconds) are the only way to update the route information unless the updating control packet, *Join Query*, occurs. These time intervals delay the route update and create the longer end-to-end delays.

4.4.3 Protocol Comparison

To compare the each performance between DVMRP and ODMRP, the 5-user case is used. The 5-user case does not have the location argument. There is a ground station at a site, which shows the even distribution unlike the 10, and 15-user case. The 5-user case can provide an absolute comparison condition between the protocols.

4.4.3.1 Data-to-Overhead Ratio Analysis

In Figure 22, DVMRP shows a higher data-to-overhead ratio than ODMRP. When a particular satellite failure scenario is applied, each protocol shows a different trend. DVMRP's ratio is decreasing and ODMRP's ratio is increasing after failing a satellite.

ODMRP broadcasts fewer control packets to the network when a satellite fails. The failed satellites cannot exchange *Join query* and *Join Reply* control packets. ODMRP has a *soft-state* that allows a multicast source or a receiver to stop sending a control packet when they want to leave the multicast group [BaL00]. This mechanism creates fewer control packets. Additionally, lost data packets created by a failed satellite do not dramatically increase the overhead because ODMRP's mesh nodes prevent the packet

lost. Less control packets increase the data-to-overhead ratio in proportion to the number of failure satellite.

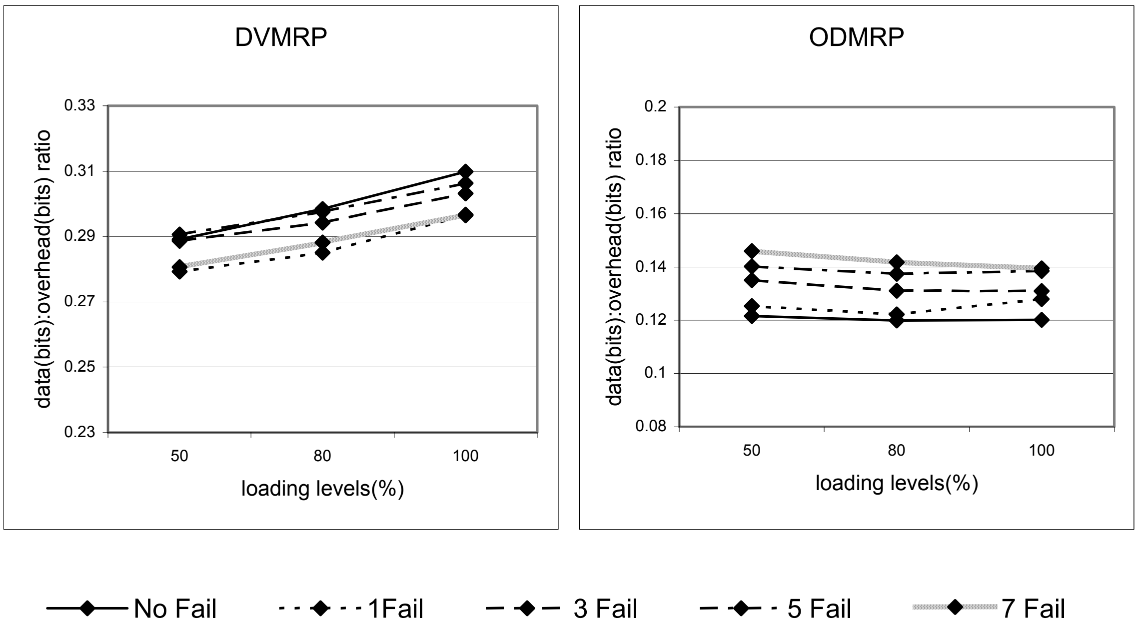


Figure 22 The Data-to-Overhead comparison between DVMRP and ODMRP

However, the lost data packets in DVMRP increase the overhead. This results in decreasing the data-to-overhead ratio. Additionally, the ground station that is in the footprint of failed satellite still receives the data packet in spite of data packet losses. To receive the data packet, DVMRP pays a cost to sustain the same vector data under the satellite failure conditions. To sustain the same connectivity under the satellite failures, additional overhead (e.g., flood and prune control packets) of creating a new tree are needed.

4.4.3.2 Received-to-Sent Ratio Analysis

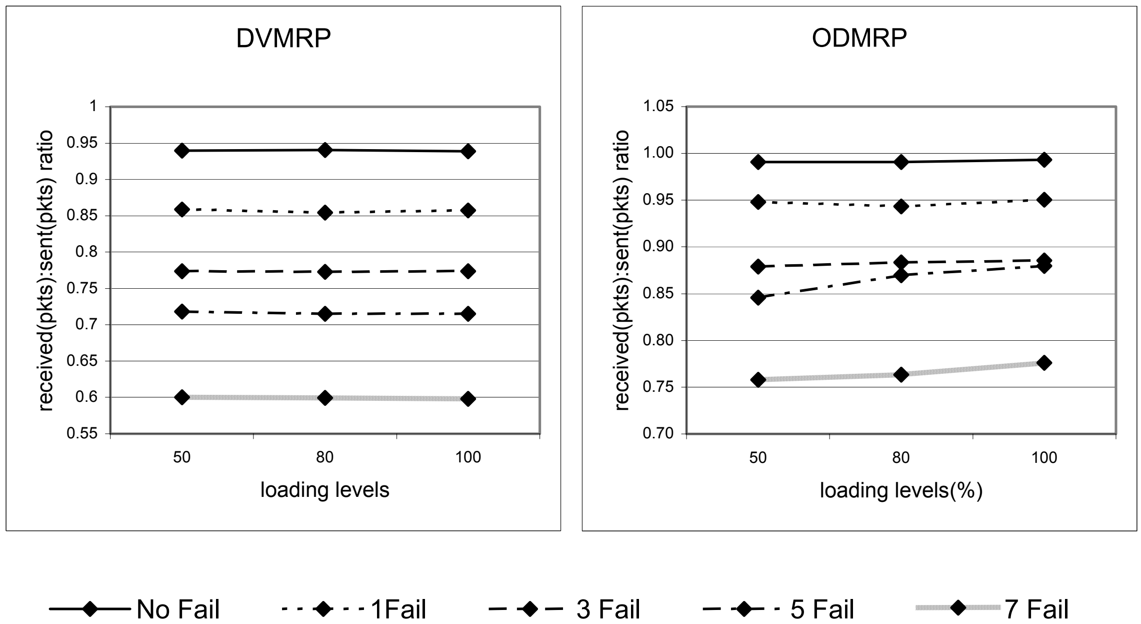


Figure 23 The Received-to-Sent Comparison between DVMRP and ODMRP

DVMRP and ODMRP show a similar trend for the received-to-sent ratio. Figure 23 presents the decreasing ratio as the number of failure satellite is increasing. Data packets transmitted from the ground stations in the footprint of failed satellites are lost. The more failure satellites, the more data packets are lost. However, robustness when satellites failure is differently observed between protocols. DVMRP has the lowest received-to-sent ratio at 0.6 while ODMRP has the lowest ratio 0.76 in the seven-satellite failure case. This result shows that ODMRP has the higher reliability than DVMRP. The mesh of nodes in ODMRP provides the higher received-to-sent ratio while the source tree of DVMRP loses the data packets as connectivity changes.

4.4.3.3 End-to-End Delay Analysis

As the numbers of satellite failures increase, the end-to-end delay also increases for both DVMRP and ODMRP. This comes from packet rerouting time caused by failed satellites. However, each protocol shows a different trend under the satellite failure environment. DVMRP shows the increasing delay while ODMRP shows a decreasing delay as the loading level increases. Figure 24 shows these trends.

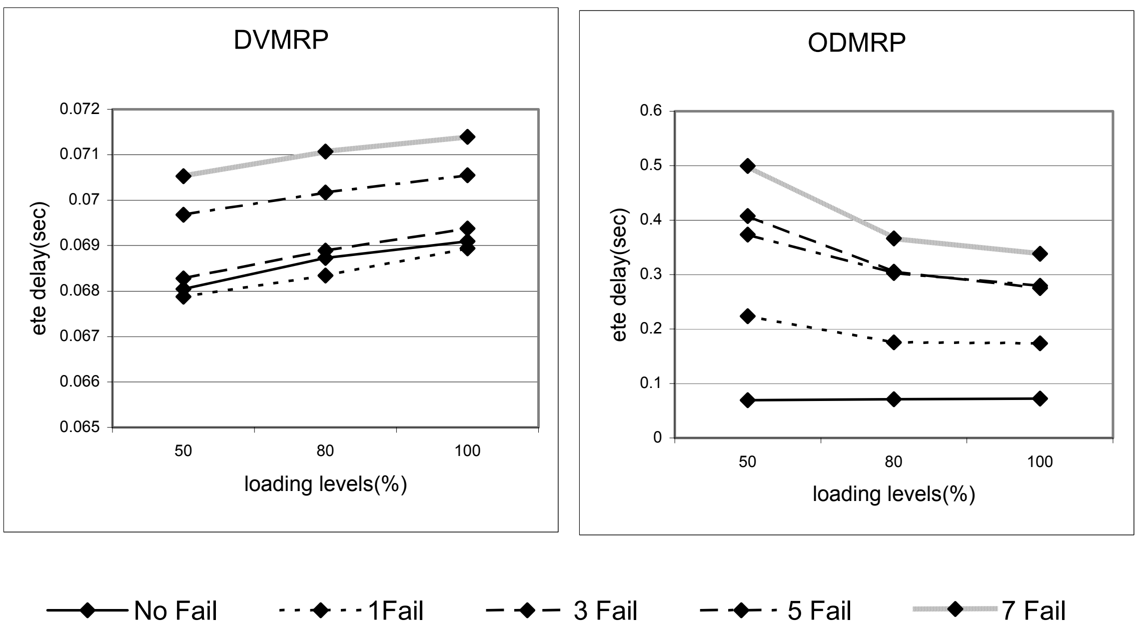


Figure 24 The End-to-End Delay Comparison between DVMRP and ODMRP

The source on demand mechanism in ODMRP may delay route updating at lower loading levels. As the number of satellite failures is increasing, the old route information delays the packet delivery from a source to a receiver. Unlike ODMRP, DVMRP satisfies the queuing delay as the loading level increase. DVMRP has a typical source tree.

ODMRP shows the dramatic increase in delay while DVMRP shows a slight increase in delay when a satellite fails. This result comes from the timing configurations based in each protocol. Each protocol has its own route refresh function to update old route information when a satellite fails to route a data packet. A *flash update* in DVMRP and *forwarding group time out,* and *route time-out* in ODMRP are the examples. Flash update is ten seconds, the forwarding group time-out is 150 seconds and the route time-out is 100 seconds. Hence, ODMRP takes the longer route-refreshing interval to update old route information than DVMRP. This results in dramatically increasing delay.

4.5 Conclusions

Both protocols display unique characteristics in the high membership scenario and satellite failure scenario. In the high membership scenario, ODMRP has advantages using the metric of received-to-sent ratio and the end-to-end delay. The mesh-based tree of ODMRP provides more reliable packet delivery and less end-to-end delay than DVMRP as the complexity of the route increases with a high number of users. However, the DVMRP requires less overhead than ODMRP by simply creating a source tree. In the satellite failure scenario, strategy one has a greater impact on performance than strategy two in DVMRP scenario, whereas strategy two has a more severe impact than strategy one in ODMRP. These two different failure scenarios reveal that DVMPR does not dynamically configure a route, whereas ODMRP does when multiple satellites fail. As expected, ODMRP showed a higher reliability of packet delivery than DVMRP in the presence of failed satellites. However, the on-demand procedure and timing

configuration of ODMRP skew the end-to-end delay as the number of failed satellites increase.

Chapter 5: Conclusions

5.1 Restatement of Research Goal

The goal of this research was to expand Thomas' research of comparing two multicast protocols for a LEO multicast satellite network. The first is the Distance Vector Multicast Routing Protocol (DVMRP) and the other is the On Demand Multicast Routing Protocol (ODMRP). These protocols are examined under various simulation environments (i.e., large group membership density and satellite failure conditions).

5.2 Research Contributions

Thomas [Tho01] analyzed DVMRP and ODMRP in a LEO satellite constellation network. Thomas' research was limited to analyzing small group membership density and a single satellite failure condition for verifying the robustness of a LEO satellite network. One of the most significant contributions of this research was the analysis of a LEO satellite network's robustness against multiple failed satellites. Two different algorithms for choosing failed satellites revealed a characteristic of the protocols in more detail against a partially broken network. Another significant result of this research was the analysis of the large group membership density in a LEO satellite network. In particular, a large group membership density in ODMRP was evaluated in order to show generality for group membership density. These two significant results provided a more complete assessment of the Distance Vector Multicast Routing Protocol (DVMRP) and the On Demand Multicast Routing Protocol (ODMRP) in a LEO satellite network.

5.3 Conclusions

Each protocol has its own advantages and disadvantages. Each protocol can be a viable choice for a LEO satellite network depending on the situation.

In a large membership density, ODMRP seems a logical choice regardless of bandwidth usage. ODMRP outperformed DVMRP in reliable packet delivery and end-to-end delay scenario. However, ODMRP had a smaller data-to-overhead ratio (approximately 23%) than DVMRP. ODMRP requires high bandwidth usage for creating mesh-based trees.

In multiple satellite failure conditions, ODMRP has the most reliable packet delivery ratio. The ODMRP also increases packet delivery ratio as the group membership increases. However, ODMRP showed an enormous end-to-end delay in severe satellite failure condition. In particular, the end-to-end delay at low loading levels dramatically increased, which is undesirable in real-time communications. In contrast, DVMRP suffered broken routes and changes in satellite failure conditions. It demonstrated less reliable packet delivery than ODMRP (approximately 60% versus 76% for the 5-user case). DVMRP showed scalable and stable end-to-end delay under multiple failed satellite conditions.

5.4 Future Research

The OPNET simulation model used in this research can be expanded to study an alternate protocol. In particular, Protocol Independent Multicast–Dense Mode (PIM-DM) is a possibility. The ‘Broadcast and Prune’ mechanism is used in the DVMRP and PIM-DM in order to create a multicast tree. However, PIM-DM uses a unicast routing

table to check Reverse Path Forwarding (RPF) while DVMRP uses its own routing table built from the route report process. PIM-DM can be an alternative to replace DVMRP.

Another future research area is the analysis of other LEO satellite constellations such as Teledesic. The Iridium project used as the framework for investigation is no longer commercially viable. It seems impossible to compare the result of research with a real-world system. Teledesic is also a LEO satellite constellation network utilizing 288 satellites. It is expected to be in service in 2005. The study of multicast routing algorithms for Teledesic can provide a realistic evaluation of LEO multicast satellite networks.

Appendix A. Data Tables

Table 13 ODMRP, High Membership, Urban Distribution (Sparse)

Users	Loading level	Data to Overhead		Received-to-sent		End to End Delay	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
40	50	0.1963	0.0010	0.9353	0.0008	0.0652	0.0001
	80	0.1956	0.0008	0.9284	0.0004	0.0669	0.0000
	100	0.1949	0.0005	0.9234	0.0005	0.0680	0.0000
60	50	0.2155	0.0012	0.9264	0.0009	0.0658	0.0001
	80	0.2134	0.0004	0.9181	0.0014	0.0669	0.0001
	100	0.2125	0.0011	0.9106	0.0009	0.0684	0.0000
80	50	0.2022	0.0007	0.9649	0.0007	0.0653	0.0001
	80	0.2012	0.0004	0.9637	0.0003	0.0664	0.0001
	100	0.2008	0.0003	0.9632	0.0005	0.0671	0.0001

Table 14 ODMRP, High Membership, Random Distribution (Dense)

Users	Loading level	Data to Overhead		Received-to-sent		End to End Delay	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
40	50	0.1988	0.0007	0.9764	0.0004	0.0520	0.0001
	80	0.1967	0.0004	0.9726	0.0002	0.0535	0.0000
	100	0.1966	0.0001	0.9704	0.0002	0.0544	0.0000
60	50	0.2295	0.0002	0.9872	0.0003	0.0567	0.0003
	80	0.2275	0.0003	0.9850	0.0010	0.0567	0.0001
	100	0.2264	0.0002	0.9822	0.0008	0.0577	0.0001
80	50	0.2390	0.0006	0.9909	0.0005	0.0541	0.0006
	80	0.2368	0.0004	0.9882	0.0003	0.0544	0.0004
	100	0.2364	0.0003	0.9869	0.0003	0.0550	0.0003

Table 15 DVMRP, Received-to-Sent Ratio, Strategy 1 and 2

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure			
						Strategy 1		Strategy 2	
		$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
5	50	0.9397	0.0016	0.8587	0.0065	0.7735	0.0052	0.8184	0.0047
	80	0.9404	0.0028	0.8542	0.0031	0.7726	0.0033	0.8137	0.0051
	100	0.9387	0.0043	0.8571	0.0054	0.7736	0.0088	0.8167	0.0031
10	50	0.9084	0.0027	0.9076	0.0027	0.8215	0.0026	0.8491	0.0193
	80	0.9087	0.0011	0.9070	0.0022	0.8223	0.0012	0.8577	0.0034
	100	0.9087	0.0027	0.9064	0.0020	0.8200	0.0019	0.8578	0.0015
15	50	0.9051	0.0026	0.9049	0.0021	0.7935	0.0024	0.8224	0.0024
	80	0.9030	0.0032	0.9049	0.0028	0.7918	0.0030	0.8221	0.0021
	100	0.9020	0.0025	0.9010	0.0046	0.7909	0.0029	0.8211	0.0018

Table 16 DVMRP, Data-to-Overhead Ratio, Satellite Failures

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure		5-Satellite Failure		7-Satellite Failure	
		$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
5	50	0.2892	0.0022	0.2792	0.0029	0.2886	0.0036	0.2906	0.0019	0.2807	0.0011
	80	0.2984	0.0045	0.2851	0.0043	0.2942	0.0032	0.2975	0.0017	0.2882	0.0032
	100	0.3098	0.0047	0.2965	0.0053	0.3032	0.0044	0.3063	0.0031	0.2967	0.0033
10	50	0.3881	0.0019	0.3982	0.0027	0.4018	0.0016	0.4034	0.0009	0.4003	0.0009
	80	0.3900	0.0020	0.3995	0.0039	0.4034	0.0039	0.4055	0.0019	0.4026	0.0024
	100	0.3928	0.0033	0.4037	0.0032	0.4068	0.0022	0.4108	0.0009	0.4067	0.0017
15	50	0.4405	0.0015	0.4459	0.0034	0.4358	0.0027	0.4368	0.0029	0.4449	0.0037
	80	0.4416	0.0025	0.4479	0.0039	0.4385	0.0018	0.4391	0.0036	0.4458	0.0014
	100	0.4397	0.0036	0.4473	0.0031	0.4373	0.0043	0.4428	0.0018	0.4481	0.0033

Table 17 DVMRP, Received-to-Sent Ratio, Satellite Failures

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure		5-Satellite Failure		7-Satellite Failure	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
5	50	0.9397	0.0016	0.8587	0.0065	0.7735	0.0052	0.7184	0.0029	0.6002	0.0062
	80	0.9404	0.0028	0.8542	0.0031	0.7726	0.0033	0.7153	0.0061	0.5994	0.0022
	100	0.9387	0.0043	0.8571	0.0054	0.7736	0.0088	0.7151	0.0037	0.5981	0.0021
10	50	0.9084	0.0027	0.9076	0.0027	0.8215	0.0026	0.7873	0.0028	0.7209	0.0019
	80	0.9087	0.0011	0.9070	0.0022	0.8223	0.0012	0.7873	0.0013	0.7188	0.0035
	100	0.9087	0.0027	0.9064	0.0020	0.8200	0.0019	0.7891	0.0030	0.7194	0.0032
15	50	0.9051	0.0026	0.9049	0.0021	0.7935	0.0024	0.7953	0.0011	0.7960	0.0012
	80	0.9030	0.0032	0.9049	0.0028	0.7918	0.0030	0.7954	0.0008	0.7957	0.0021
	100	0.9020	0.0025	0.9010	0.0046	0.7909	0.0029	0.7958	0.0004	0.7941	0.0020

Table 18 DVMRP, End-to-End Delay, Satellite Failures

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure		5-Satellite Failure		7-Satellite Failure	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
5	50	0.0680	0.0002	0.0679	0.0004	0.0683	0.0004	0.0697	0.0003	0.0705	0.0005
	80	0.0687	0.0004	0.0683	0.0004	0.0689	0.0003	0.0702	0.0003	0.0711	0.0002
	100	0.0691	0.0005	0.0689	0.0004	0.0694	0.0005	0.0706	0.0003	0.0714	0.0004
10	50	0.0656	0.0001	0.0682	0.0001	0.0689	0.0001	0.0696	0.0000	0.0697	0.0001
	80	0.0662	0.0001	0.0688	0.0001	0.0695	0.0001	0.0702	0.0001	0.0701	0.0002
	100	0.0666	0.0002	0.0692	0.0002	0.0698	0.0001	0.0707	0.0002	0.0705	0.0002
15	50	0.0683	0.0001	0.0709	0.0000	0.0707	0.0002	0.0714	0.0001	0.0711	0.0001
	80	0.0688	0.0001	0.0714	0.0001	0.0712	0.0000	0.0720	0.0001	0.0716	0.0000
	100	0.0691	0.0001	0.0718	0.0002	0.0715	0.0001	0.0724	0.0001	0.0719	0.0001

Table 19 ODMRP, Received-to-Sent Ratio, Strategy 1 and 2

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure			
						Strategy 1		Strategy 2	
		$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
5	50	0.9908	0.0038	0.9482	0.0041	0.8857	0.0101	0.8789	0.0108
	80	0.9909	0.0045	0.9434	0.0036	0.9017	0.0069	0.8835	0.0057
	100	0.9933	0.0007	0.9504	0.0043	0.9033	0.0050	0.8855	0.0033
10	50	0.9941	0.0019	0.9865	0.0017	0.9532	0.0015	0.9352	0.0016
	80	0.9952	0.0004	0.9871	0.0009	0.9523	0.0012	0.9349	0.0007
	100	0.9939	0.0005	0.9863	0.0015	0.9507	0.0009	0.9322	0.0031
15	50	0.9959	0.0013	0.9969	0.0002	0.9902	0.0005	0.9758	0.0005
	80	0.9942	0.0017	0.9950	0.0009	0.9880	0.0008	0.9739	0.0006
	100	0.9942	0.0007	0.9944	0.0009	0.9864	0.0010	0.9720	0.0011

Table 20 ODMRP, Data-to-Overhead Ratio, Satellite Failures

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure		5-Satellite Failure		7-Satellite Failure	
		$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
5	20	0.1381	0.0051	0.1414	0.0054	0.1483	0.0019	0.1521	0.0020	0.1566	0.0028
	50	0.1215	0.0032	0.1253	0.0029	0.1351	0.0026	0.1402	0.0039	0.1459	0.0027
	80	0.1200	0.0031	0.1222	0.0049	0.1311	0.0061	0.1374	0.0045	0.1417	0.0048
	100	0.1201	0.0015	0.1279	0.0013	0.1309	0.0072	0.1384	0.0045	0.1395	0.0057
10	20	0.1449	0.0013	0.1453	0.0017	0.1523	0.0020	0.1575	0.0024	0.1663	0.0029
	50	0.1307	0.0009	0.1314	0.0010	0.1399	0.0007	0.1438	0.0010	0.1540	0.0012
	80	0.1276	0.0006	0.1291	0.0011	0.1378	0.0008	0.1429	0.0014	0.1525	0.0013
	100	0.1277	0.0009	0.1297	0.0008	0.1418	0.0009	0.1483	0.0008	0.1596	0.0015
15	20	0.1542	0.0027	0.1555	0.0020	0.1591	0.0018	0.1627	0.0024	0.1665	0.0009
	50	0.1404	0.0008	0.1417	0.0007	0.1463	0.0005	0.1508	0.0009	0.1580	0.0004
	80	0.1384	0.0010	0.1401	0.0009	0.1453	0.0005	0.1508	0.0004	0.1582	0.0005
	100	0.1390	0.0006	0.1392	0.0004	0.1449	0.0006	0.1516	0.0005	0.1591	0.0005

Table 21 ODMRP, Received-to-Sent Ratio, Satellite Failures

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure		5-Satellite Failure		7-Satellite Failure	
		$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s
5	20	0.9846	0.0050	0.9450	0.0060	0.8644	0.0109	0.8372	0.0072	0.7564	0.0069
	50	0.9908	0.0038	0.9482	0.0041	0.8789	0.0108	0.8457	0.0076	0.7580	0.0073
	80	0.9909	0.0045	0.9434	0.0036	0.8835	0.0057	0.8697	0.0106	0.7633	0.0098
	100	0.9933	0.0007	0.9504	0.0043	0.8855	0.0033	0.8797	0.0044	0.7760	0.0097
10	20	0.9941	0.0025	0.9861	0.0027	0.9373	0.0025	0.9157	0.0030	0.9177	0.0027
	50	0.9941	0.0019	0.9865	0.0017	0.9352	0.0016	0.9171	0.0022	0.9146	0.0017
	80	0.9952	0.0004	0.9871	0.0009	0.9349	0.0007	0.9177	0.0004	0.9147	0.0011
	100	0.9939	0.0005	0.9863	0.0015	0.9322	0.0031	0.9155	0.0009	0.9117	0.0010
15	20	0.9953	0.0023	0.9955	0.0015	0.9771	0.0005	0.9226	0.0008	0.9188	0.0004
	50	0.9959	0.0013	0.9969	0.0002	0.9758	0.0005	0.9203	0.0010	0.9153	0.0003
	80	0.9942	0.0017	0.9950	0.0009	0.9739	0.0006	0.9172	0.0013	0.9112	0.0010
	100	0.9942	0.0007	0.9944	0.0009	0.9720	0.0011	0.9149	0.0015	0.9084	0.0013

Table 22 ODMRP, End-to-End Delay, Satellite Failures

Users	Loading Levels (%)	Non-Satellite Failure		1-Satellite Failure		3-Satellite Failure		5-Satellite Failure		7-Satellite Failure	
		$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s	$\overline{x}$	s
5	20	0.0673	0.0005	0.4372	0.0910	0.8331	0.0407	0.8448	0.0205	1.1014	0.0279
	50	0.0690	0.0001	0.2236	0.0388	0.4077	0.0192	0.3736	0.0126	0.4997	0.0165
	80	0.0709	0.0002	0.1758	0.0271	0.3053	0.0107	0.3028	0.0118	0.3661	0.0205
	100	0.0723	0.0003	0.1737	0.0180	0.2753	0.0109	0.2795	0.0102	0.3380	0.0127
10	20	0.0608	0.0002	0.0668	0.0016	0.6211	0.0174	0.8203	0.0099	0.8194	0.0096
	50	0.0622	0.0001	0.0655	0.0004	0.2988	0.0051	0.3811	0.0033	0.3859	0.0023
	80	0.0638	0.0001	0.0669	0.0004	0.2199	0.0047	0.2758	0.0031	0.2796	0.0029
	100	0.0653	0.0002	0.0682	0.0004	0.1965	0.0037	0.2488	0.0037	0.2508	0.0028
15	20	0.0628	0.0000	0.0644	0.0000	0.2759	0.0088	0.5604	0.0099	0.5566	0.0097
	50	0.0645	0.0021	0.0644	0.0000	0.1505	0.0035	0.2617	0.0039	0.2636	0.0041
	80	0.0656	0.0005	0.0664	0.0001	0.1233	0.0024	0.1928	0.0022	0.1959	0.0023
	100	0.0676	0.0001	0.0678	0.0001	0.1161	0.0017	0.1741	0.0017	0.1771	0.0018

Appendix B. ANOVA Table

*** Example** (α = significance level)

Source of Variation	Sum of Squares	Df	Mean Square	F	P-value	F critical value (α)
Treatments	$SSTr$	$I-1$	$MSTr$	$f = \frac{MSTr}{MSE}$	Area under F curve to right of f	$F_{\alpha, I-1, I(J-1)}$
Error	SSE	$I(J-1)$	MSE			
Total	SST	$IJ-1$				

Table 23 DVMRP, 5-user, Data-to-Overhead, in No, 3 and 5 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	8.5E-06	2	4.3E-06	0.588	0.575	4.256
	Error	6.5E-05	9	7.2E-06			
	Total	7.4E-05	11				
80%	Treatments	4E-05	2	2E-05	1.783	0.223	4.256
	Error	0.0001	9	1.1E-05			
	Total	0.00014	11				
100%	Treatments	8.8E-05	2	4.4E-05	2.569	0.131	4.256
	Error	0.00015	9	1.7E-05			
	Total	0.00024	11				

Table 24 DVMRP, 5-user, Data-to-Overhead, in 3 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	0.00013	1	0.00013	17.71	0.006	5.987
	Error	4.3E-05	6	7.2E-06			
	Total	0.00017	7				
80%	Treatments	7.2E-05	1	7.2E-05	7.089	0.0374	5.987
	Error	6.1E-05	6	1E-05			
	Total	0.00013	7				
100%	Treatments	8.6E-05	1	8.6E-05	5.663	0.055	5.987
	Error	9.1E-05	6	1.5E-05			
	Total	0.00018	7				

Table 25 DVMRP, 5-user, Data-to-Overhead, in 1 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	4E-06	1	4E-06	0.811	0.402	5.987
	Error	3E-05	6	5E-06			
	Total	3.4E-05	7				
80%	Treatments	1.9E-05	1	1.9E-05	1.365	0.287	5.987
	Error	8.6E-05	6	1.4E-05			
	Total	0.00011	7				
100%	Treatments	8.1E-08	1	8.1E-08	0.004	0.951	5.987
	Error	0.00012	6	1.9E-05			
	Total	0.00012	7				

Table 26 DVMRP, 10-user, Data-to-Overhead, in 3 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	4.8E-06	1	4.8E-06	2.833	0.143	5.987
	Error	1E-05	6	1.7E-06			
	Total	1.5E-05	7				
80%	Treatments	1.52E-06	1	1.5E-06	0.147	0.715	5.987
	Error	6.2E-05	6	1E-05			
	Total	6.4E-05	7				
100%	Treatments	1.21E-08	1	1.2E-08	0.003	0.958	5.987
	Error	2.4E-05	6	3.9E-06			
	Total	2.4E-05	7				

Table 27 DVMRP, 10-user, Data-to-Overhead, in No and 1 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	0.0002	1	0.0002	37.054	9E-04	5.9874
	Error	3.3E-05	6	5.5E-06			
	Total	0.00024	7				
80%	Treatments	0.00018	1	0.00018	18.739	0.005	5.9874
	Error	5.76E-05	6	9.6E-06			
	Total	0.000237	7				
100%	Treatments	0.00024	1	0.00024	22.526	0.003	5.9874
	Error	6.3E-05	6	1.1E-05			
	Total	0.0003	7				

Table 28 DVMRP, 15-user, Data-to-Overhead, in No, 3 and 5 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	5E-05	2	2E-05	4.124	0.054	4.256
	Error	5E-05	9	6E-06			
	Total	1E-04	11				
80%	Treatments	2E-05	2	1E-05	1.524	0.269	4.256
	Error	7E-05	9	7E-06			
	Total	9E-05	11				
100%	Treatments	6E-05	2	3E-05	2.655	0.124	4.256
	Error	1E-04	9	1E-05			
	Total	2E-04	11				

Table 29 DVMRP, 15-user, Data-to-Overhead, in No and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	3.8E-05	1	3.8E-05	4.707	0.073	5.987
	Error	4.9E-05	6	8.2E-06			
	Total	8.7E-05	7				
80%	Treatments	3.4E-05	1	3.4E-05	8.178	0.029	5.987
	Error	2.5E-05	6	4.2E-06			
	Total	5.9E-05	7				
100%	Treatments	0.00014	1	0.00014	11.93	0.014	5.987
	Error	7.1E-05	6	1.2E-05			
	Total	0.00021	7				

Table 30 DVMRP, 15-user, Data-to-Overhead, in 1 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	4.6E-06	1	4.6E-06	0.369	0.566	5.987
	Error	7.5E-05	6	1.2E-05			
	Total	7.9E-05	7				
80%	Treatments	9.2E-06	1	9.2E-06	1.085	0.338	5.987
	Error	5.1E-05	6	8.5E-06			
	Total	6E-05	7				
100%	Treatments	1.3E-06	1	1.3E-06	0.124	0.736	5.987
	Error	6.2E-05	6	1E-05			
	Total	6.3E-05	7				

Table 31 DVMRP, 15-user, Received-to-Sent, in 3, 5 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	1.3E-05	2	6.4E-06	2.292	0.157	4.256
	Error	2.5E-05	9	2.8E-06			
	Total	3.8E-05	11				
80%	Treatments	3.8E-05	2	1.9E-05	3.969	0.058	4.256
	Error	4.3E-05	9	4.7E-06			
	Total	8E-05	11				
100%	Treatments	4.9E-05	2	2.5E-05	5.837	0.024	4.256
	Error	3.8E-05	9	4.2E-06			
	Total	8.7E-05	11				

Table 32 DVMRP, 5-user, End-to-End Delay, in No, 1 and 3 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	3.3E-07	2	1.6E-07	1.326	0.313	4.256
	Error	1.1E-06	9	1.2E-07			
	Total	1.4E-06	11				
80%	Treatments	6.3E-07	2	3.2E-07	2.829	0.1113	4.256
	Error	1E-06	9	1.1E-07			
	Total	1.6E-06	11				
100%	Treatments	3.9E-07	2	2E-07	0.918	0.434	4.256
	Error	1.9E-06	9	2.1E-07			
	Total	2.3E-06	11				

Table 33 DVMRP, 5-user, End-to-End Delay, in 3 and 5 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	3.9E-06	1	3.9E-06	32.54	0.001	5.987
	Error	7.2E-07	6	1.2E-07			
	Total	4.6E-06	7				
80%	Treatments	3.3E-06	1	3.3E-06	39.81	0.0007	5.987
	Error	5E-07	6	8.3E-08			
	Total	3.8E-06	7				
100%	Treatments	2.8E-06	1	2.8E-06	13.91	0.0097	5.987
	Error	1.2E-06	6	2E-07			
	Total	4E-06	7				

Table 34 DVMRP, 10-user, End-to-End Delay, in 5 and 7satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	1.4E-08	1	1.4E-08	1.520	0.264	5.987
	Error	5.6E-08	6	9.4E-09			
	Total	7.1E-08	7				
80%	Treatments	1.5E-08	1	1.5E-08	0.695	0.436	5.987
	Error	1.3E-07	6	2.15E-08			
	Total	1.4E-07	7				
100%	Treatments	6.4E-08	1	6.4E-08	2.30	0.180	5.987
	Error	1.7E-07	6	2.8E-08			
	Total	2.3E-07	7				

Table 35 DVMRP, 10-user, End-to-End Delay, in No and 1satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	1.3E-05	1	1.3E-05	1026.8	6E-08	5.9874
	Error	7.8E-08	6	1.3E-08			
	Total	1.3E-05	7				
80%	Treatments	1.3E-05	1	1.32E-05	1528.6	1.9E-08	5.9874
	Error	5.2E-08	6	8.66E-09			
	Total	1.3E-05	7				
100%	Treatments	1.3E-05	1	1.3E-05	375.9	1E-06	5.987
	Error	2.1E-07	6	3.4E-08			
	Total	1.3E-05	7				

Table 36 DVMRP, 15-user, End-to-End Delay, in 1 and 3 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	4E-08	1	4E-08	2.608	0.157	5.987
	Error	9.2E-08	6	1.5E-08			
	Total	1.3E-07	7				
80%	Treatments	1.1E-07	1	1.1E-07	30.92	0.001	5.987
	Error	2.2E-08	6	3.7E-09			
	Total	1.4E-07	7				
100%	Treatments	1.2E-07	1	1.2E-07	5.102	0.065	5.987
	Error	1.4E-07	6	2.4E-08			
	Total	2.7E-07	7				

Table 37 DVMRP, 15-user, End-to-End Delay, in 1 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
50%	Treatments	7.6E-08	1	7.6E-08	10.94	0.016	5.987
	Error	4.2E-08	6	6.9E-09			
	Total	1.2E-07	7				
80%	Treatments	9.3E-08	1	9.3E-08	23.2	0.003	5.987
	Error	2.4E-08	6	4E-09			
	Total	1.2E-07	7				
100%	Treatments	3.4E-08	1	3.4E-08	1.262	0.304	5.987
	Error	1.6E-07	6	2.7E-08			
	Total	2.7E-07	7				

Table 38 ODMRP, 15-user, Received-to-Sent, in No and 1 satellite failure

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
20%	Treatments	9E-08	1	9E-08	0.024	0.882	5.987
	Error	2.2E-05	6	3.7E-06			
	Total	2.3E-05	7				
50%	Treatments	2.1E-06	1	2.1E-06	2.217	0.187	5.987
	Error	5.6E-06	6	9.3E-07			
	Total	7.7E-06	7				
80%	Treatments	1.2E-06	1	1.2E-06	0.636	0.455	5.987
	Error	1.1E-05	6	1.9E-06			
	Total	1.3E-05	7				
100%	Treatments	6.6E-08	1	6.6E-08	0.103	0.7595	5.987
	Error	3.9E-06	6	6.5E-07			
	Total	3.9E-06	7				

Table 39 ODMRP, 10-user, End-to-End Delay, in 5 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
20%	Treatments	0.001	1	0.0011	0.825	0.399	5.987
	Error	0.008	6	0.0013			
	Total	0.009	7				
50%	Treatments	4.6E-05	1	4.6E-05	5.645	0.055	5.987
	Error	4.9E-05	6	8.1E-06			
	Total	9.5E-05	7				
80%	Treatments	2.8E-05	1	2.8E-05	3.148	0.126	5.987
	Error	5.3E-05	6	8.9E-06			
	Total	8.1E-05	7				
100%	Treatments	8E-06	1	8E-06	0.733	0.425	5.987
	Error	6.6E-05	6	1.1E-05			
	Total	7.4E-05	7				

Table 40 ODMRP, 10-user, End-to-End Delay, in 3 and 5 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
20%	Treatments	0.07937	1	0.079	395.691	1.05E-06	5.987
	Error	0.0012	6	0.0002			
	Total	0.08058	7				
50%	Treatments	0.0136	1	0.014	728	2E-07	5.987
	Error	0.0001	6	2E-05			
	Total	0.0137	7				
80%	Treatments	0.0063	1	0.006	397.36	1E-06	5.987
	Error	9E-05	6	2E-05			
	Total	0.0063	7				
100%	Treatments	0.00548	1	0.005	402.185	9.98E-07	5.987
	Error	8.2E-05	6	1.36E-05			
	Total	0.00556	7				

Table 41 ODMRP, 15-user, End-to-End Delay, in 5 and 7 satellite failures

Loading Level	Source of Variation	Sum of Squares	df	Mean Square	F	P-value	F critical value (0.05)
20%	Treatments	3E-05	1	2.9E-05	0.298	0.605	5.987
	Error	0.0006	6	9.6E-05			
	Total	0.0006	7				
50%	Treatments	6.7E-06	1	6.7E-06	0.417	0.542	5.987
	Error	9.7E-05	6	1.6E-05			
	Total	0.0001	7				
80%	Treatments	1.9E-05	1	1.9E-05	3.946	0.094	5.987
	Error	3E-05	6	4.9E-06			
	Total	4.9E-05	7				
100%	Treatments	1.8E-05	1	1.8E-05	5.881	0.052	5.987
	Error	1.8E-05	6	3.1E-06			
	Total	3.6E-05	7				

BIBLIOGRAPHY

[BaL00] Bae, Sang Ho, S. J. Lee, W. Su, and M. Gerla, "The Design, Implementation and Performance Evaluation of the On-Demand Multicast Routing Protocol in Multihop Wireless Networks," IEEE Network, pp. 70-77, January/February 2000.

[Bal97] Ballardie, A., "Core Based Trees (CBT version2) Multicast Routing," RFC2189, Internet Engineering Task Force, September 1997.

[BoL98] Bommaiah, E., M. Liu, A. McAuley, and R. Talpade. "AMRoute: Ad hoc multicast routing protocol," Draft-ietc-manet-amroute-00.txt, August 1998.

[Cor99] Corson, M. S., "Mobile ad hoc networking (MANET): Routing protocol performance issues and evaluation considerations," RFC 2501, January 1999.

[ChR89] Cheng, Riley, and Kumar, "A Loop-Free Bellman-Ford Routing Protocol Without Bouncing Effect," SIGCOMM 1989, pp. 224-236

[ChW98] Chickarmane, V., C. L. Williamson, R. B. Bunt, and W. Mackrell, " Multicast support for mobile hosts using mobile IP: Design issues and proposed architecture," Mobile Networks and Applications, Vol. 3, No.4, 1998.

[[Dee89] Deering, S., "Host extensions for IP multicasting." RFC 1112, August 1989.

[Dev99] Devore, Jay L., *Probability and Statistics: For Engineering and the Sciences*, Duxbury, California 1999.

[Fen97] Fenner, W., "Internet Group Management Protocol, Version2," RFC 2236, November 1997.

[Fos98] Fossa, C. E., "A performance analysis of the iridium low earth orbit satellite system," Master's thesis, AFIT/GCE/ENG/98M-04, Air Force Institute of Technology, 1998.

[Jai91] Jain, Raj, *The Art of Computer Systems Performance Analysis: Techniques for Experimental Design, Measurement, Simulation, and Modeling*, John Wiley & Sons, INC. New York, 1991.

[Jam98] Jamalipour, Abbas, *Low Earth Orbital Satellites for Personal Communication Networks*. Norwood, Massachusetts. Artech House, 1998.

[LeS00] Lee, S.J., W. Su, J. Hsu, M. Gerla, and R. Bagrodia, "A performance comparison study of ad hoc wireless multicast protocols," in Proceedings of IEEE Infocom, 2000.

[Mau98] Maufer, T., *Deploying IP Multicast in the Enterprise*, Prentice-Hall, Upper Saddle River, 1998.

[May94] May, J., "Multicast Extension to OSPF," RFC1584, Mar 1994.

[Mul00] Muller, A., "A comparative analysis of proposed mobility support schemes for IP multicast," Master's thesis, AFIT/GCS/ENG/00J-02, Air Force Institute of Technology, 2000.

[Per96a] Perkins, C., "IP mobility support," RFC 2002, October 1996.

[Per96b] Perkins, C., "IP Encapsulation within IP", RFC 2003, October 1996.

[Per98] Perlman, R. et al., "Simple Multicast: A Design For Simple, Low-Overhead Multicast,"draft-perlman-simple-multicast-01.txt, 1998.

[Pra99] Pratt, S. R., "A performance analysis of dynamic routing algorithms in an Iridium-like low earth orbit satellite system," Master's thesis, AFIT/GCE/ENG/99M-04, Air Force Institute of Technology, 1999.

[Ram00] Ramalho, M., "Intra-and inter-domain multicasting routing protocols: A survey and taxonomy," IEEE Communications: Surveys and Tutorials, January-March 2000.

[Rod95] Roddy, D., Satellite Communications, New York. McGraw-Hill, 1995,

[SaM00] Sahasrabuddhe, Laxman H. and Biswanath Mukherjee, "Multicast Routing Algorithms and Protocols: A Tutorial," IEEE Network, pp. 90-102, January/February 2000.

[Sol98] Solomon, J. D., Mobile IP: the Internet Unplugged. Upper Saddle River, New Jersey: Prentice Hall, 1988.

[Tho01] Thomas, Ryan W., "Multicast algorithms for mobile satellite communication networks," Master's thesis, AFIT/GCE/ENG/01M-04, Air Force Institute of Technology, 2001.

[TsM95] Tsai, K. and R. Ma, "Darting: A cost effective routing alternative for large space-based dynamic topology networks," in MILCOM '95, pp. 682-687, 1995.

[WaH00] Wang, Bin and Jennifer C. Hou, "Multicast routing and Its QoS Extension: Problems, Algorithms, and Protocol," IEEE Network, pp. 22-36, January/February 2000.

[WuT98] Wu, C.W., Y. C. Tay, and C-K. Toh, "Ad hoc Multicast Routing protocol utilizing Increasing id-numbers (AMRIS) Fundamental Specification," draft-ietf-manet-amris-spec-00.txt, November 1998.

VITA

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14. ABSTRACT

In the rapidly changing environment of mobile communications, the importance of low earth orbit satellites (LEOsats) networks will increase due to their global visibility and connection. Multicasting is an effective communication method for a LEO network because it has lower network traffic (i.e., one-to-many transmissions). This research examines the system performance of two terrestrially-based multicasting protocols: the Distance Vector Multicast Routing Protocol (DVMRP) and the On Demand Multicast Routing Protocol (ODMRP). These two protocols are simulated with different group membership densities and in the presence of satellite failures. Two different algorithms are developed to select critical satellites for degrading the LEO network constellation. Results show that ODMRP effectively reconfigures routes with large group membership density and in the satellite failure conditions. Results also show that the ODMRP provides reliable packet delivery. However, ODMRP has an enormous end-to-end delay in severe failure conditions. In contrast, DVMRP suffered broken routes and complexity in large group membership densities and satellite failure conditions. It demonstrated a less reliable packet delivery than ODMRP. DVMRP has the advantage of scalable and stable end-to-end delay under multiple failed satellite conditions.

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